INVESTIGATION INTO WHEEL WEAR, WHEEL LOADING AND RANDOM VIBRATION DURING SURFACE GRINDING

by

A. K. S. CHOUDHARY

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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INVESTIGATION INTO WHEEL WEAR, WHEEL LOADING AND RANDOM VIBRATION DURING SURFACE GRINDING

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A. K. S. CHOUDHARY

to the

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

JULY, 1982

DEDICATED

to

MY PARENTS

CERTIFICATE

This is to certify that the work entitled " Investigation into wheel wear, wheel loading and random vibration during surface grinding" has been carried out under my supervision and has not been submitted elsewhere for the award of a degree.

8/7/82

(G.S. KAINTH)
PROFESSOR
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur
Kanpur-208016

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NOMENCLATURE

D	Depth of cut, micron
V	Grinding wheel speed, rpm
v	Table speed, m/min
N	No. of digitised samples
M	Maximum number of correlation points
t	Time, sec.
Δt	Sampling interval, sec.
T	Time period.
τ	Time delays, sec.
$R(\tau)$	Correlation function
f	Frequency, H_z.
f_p	Frequency at which peak power spectral density occur.
f_N	Natural frequency, H_z.
f_{max}	Maximum frequency, H_z.
$f(t)$, $g(t)$	Time varying functions.
$\bar{f}$, $\bar{g}$	Time averages of the functions
$\phi(f)$	Power spectral density
$\phi'(f)$	Smoothed power spectral density.
ω	Angular frequency, rad/sec.
σ_f , σ_g	Standard deviations.
σ_f^2, σ_g^2	Variance.

SYNOPSIS

Experiments are carried out under plunge cut grinding condition on a horizontal surface grinding machine. Wheel wear and wheel loading are determined by collecting debris for up grinding and down grinding conditions.

An accelerometer is used to measure random vibration signals in radial and tangential directions. The vibration signal is digitised using an analog to digital converter and stored in the magnetic tape of the computer. A computer program is developed to calculate auto correlation coefficients and power spectral density for the digitised data.

The variation of power spectral density with number of passes and its relationship with wheel wear and wheel loading is discussed.

The present investigation shows that the wheel loading has significant effect on power spectral density of the random vibration signals. Furthermore, it is possible to predict redressing condition of the wheel from measurement of the power spectral density.

The present study shows the feasibility of inprocess monitoring of vibration signals in the surface grinding process which can be used for adaptive control of the system.

CHAPTER - I

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION:

In recent years, grinding has received great attention because of ever increasing trend towards high precision in processing of varied and stronger materials. Research in the mechanics of grinding has contributed significantly in understanding its fundamental parameters. Though, the grinding process is similar to micro milling, it is unique in that the material removal is carried out by small closely spaced and randomly placed abrasive grains.

A grinding wheel is composed of a large number of small abrasive particles held together by a bonding agent. The characteristics and performance of grinding wheel depend upon a large number of significant variables such as type of abrasive grain, grain size, hardness of the wheel, structure of the wheel, type of bond etc. These parameter can be chosen to obtain a wide range of wheel types.

Majority of grinding wheels are either aluminium oxide or silicon carbide as the abrasive constituent. The grade or hardness of a wheel indicates the relative strength of bond which holds the abrasive grains in place. Increase

in the amount of bonding material increases the size and number of bond post holding each grain to its neighbours and thus increases the hardness of the wheel. The structure of a grinding wheel denotes the spacing of grains and controls the density of the wheel. The grinding wheel has intergranular space which helps to clear the wheel face from the metal surface and accommodates the chips cut by abrasive grains.

The grinding process differs fundamentally from other machining processes in the following ways,

(i) the space distribution of the cutting edges on the cutting surface of a grinding wheel is of random nature ;

(ii) the shapes, sizes, and orientation of cutting edges vary over a wide range ;

(iii) the radius of curvature of cutting edge of a grain determines chip thickness ;

(iv) grains, held elastically by bond bridges are displaced in tangential and normal directions during grinding ;

(v) the types of wear of the abrasive grains are quite different from those of other cutting tools ;

(vi) the chip thickness is very small with wide variations in shape and size ;

(vii) the temperature of abrasive grains and workpiece becomes extremely high.

During grinding, the cutting surface of the wheel and the workpiece are in a state of active physical and chemical interaction with each other. Due to wheel work interaction mettalic chips get embedded into the wheel causing wheel loading. As a result the quality of surface finish deteriorates and in some cases burns appear on the work surface.

In grinding, wear is an integral part of the process, and a wear rate that is too slow can be more undesirable in its consequences than a rapid one [7]. Attritious wear (Fig. 3B) occurs on the grain-workpiece contact surface due to formation of flat areas on the grains. This results in dulling of the abrasive grains and accounts for the glazed appearance of the grinding wheel. The cutting ability of the abrasive grains is then restored by dressing the wheel. When this type of wear is predominant, the grinding ratio, which is generally defined as the volume ratio of metal removed to wheel wear, is high.

Fracture wear (Fig. 3B), on the other hand, is due to the removal of abrasive particles from the wheel either by partial fracture of grain or by fracturing of the bond post. Fracture wear [7] results in a low grinding ratio but maintains the cutting ability of the wheel by presenting sharp cutting edges without dressing.

Grinding is used for obtaining close tolerance and high quality of surface finish on workpiece. During grinding, relative vibrations between the grinding wheel and the workpiece cause deterioration of surface finish and shorten the life of the grinding wheel.

These vibrations are of two types.

(a) Forced vibration caused by unbalance either in grinding wheel or in gearing system. These vibrations can be controlled by careful design and balancing.

(b) Self excited vibrations which arise from inhomogeneity in surface structure of grinding wheel and workpiece material, resulting in undulations on the wheel surface and workpiece. The self excited vibrations give rise to varying chip thickness for abrasive grains on the wheel surface. The variation of chip thickness may influence the life of the grinding wheel because the grains donot work evenly and many grains donot work at all.

1.2 LITERATURE REVIEW:

A large number of investigations [2, 6,10, 21, 23] have been carried out into vibrations in a grinding operation for estimating the output parameters such as surface roughness and wheel wear.

Peklenik and Kwiatkowski [9] discussed the use of random process analysis in investigating the various manufacturing systems.

Optiz and Weck [4] derived the fundamental relationship for linear time invariant system by means of the power spectral density measurement.

Martin, et al [1] measured vertical vibrations of a lathe tool and related spectral intensity to tool wear.

Raghuveer [23] applied random vibration analysis to calculate energy contained in the vibration signal for different cutting conditions in surface grinding.

Arora [20] applied statical analysis to explain the mechanics of grinding process. Whitehouse [14] suggested a graphical method for evaluating approximate values of statistical parameters of surface such as auto correlation functions etc.

Iwata and Moriwaki [3] applied accoustic emission signals detected during metal cutting to sensing tool wear and discussed feasibility of inprocess tool wear sensing. They summarised the basic characteristics of the accoustic emission signal.

Thomson [2] showed that vibration can be used to measure wheel wear and machine performance. The rate of precession of the lobes on the wheel was measured by the vibration signals.

Mitsui and Sato [13] applied the cross spectrum analysis to relate the tool vibration to the surface roughness.

Doebelin [16] described various sensors for inprocess measurement of signals.

For determining the loading of grinding wheel Konig and Aachen [8] developed a new type of sensor which measure changes in self inductance due to changes in the magnetic leakage field.

Using radiotracer technique, Shah [17] carried out loading studies under dry, plunge-cut grinding conditions for steel, brass and aluminium workpieces.

Pandey [18] obtained wheel wear from the debris collected during grinding. Kumar, et al [12] described a quantative method for measuring loading in grinding wheel. Pandey and Lal [21] evaluated the wheel life from the considerations of grinding forces, amplitude of vibrations and appearance of burns on the work surface.

Stetiu and Lal [7] studied the grinding wheel wear phenomena by analysing the debris resulting from grinding. The domain of self-dressing has been established from size distribution of the wear particles.

1.3 PRESENT WORK:

The review of literature shows that there is a need to explore the possibility of applying spectral analysis to adaptive control of grinding process. The objective of the present investigation is to determine the effect of wheel wear, loading and workpiece roughness upon the power spectral density of vibration signals in surface grinding.

CHAPTET - II

THEORETICAL ANALYSIS OF RANDOM SIGNALS

2.1 INTRODUCTION:

Random signals provide more realistic mathematical models of many physical process than do deterministic signals. Random signal is that which cannot be described [16] by a specific function of time prior to its occurrence. Harmonic analysis technique has been generalised to deal with randomly varying signals with the aid of fourier transform [15, 22]. This generalisation is quite important because random signal contains information describing the character of the system from which they emanate. It is assumed here that the random process is stationary and ergodic. A random process is said to be stationary [15] if its probability distributions are invarient under a shift of time scale. An ergodic process is one for which ensamble averages are equal to the corresponding temporal averages taken along any representative sample function. A single time or space history representing a random phenomenon is called a sample function (or a sample record when observed over a finite time or space interval). A sample record of data may be thought of as one physical realisation of a

random process. A brief treatment of random signal analysis is presented here.

2.2 AUTO CORRELATION FUNCTIONS:

The auto correlation function for random data describes the general dependence of the values of the data at one point on the values at other points.

Consider a physical process which produces a randomly time varying signal f(t). Mathematically, the auto correlation function $R_{ff}(\tau)$, is defined as,

$$R_{ff}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t)\, f(t+\tau)\, dt \qquad (2.1)$$

where T is the time period of the signal and $f(t+\tau)$ is the same signal delayed by time τ.

Important properties of auto correlation function $R_{ff}(\tau)$ are,

i) $R_{ff}(\tau)$ is an even function of τ that is
$R_{ff}(\tau) = R_{ff}(-\tau)$

ii) $R_{ff}(\tau)$ has maximum value for zero delay time that is $R_{ff}(0) \geq R_{ff}(\tau)$

iii) $R_{ff}(\tau)$ is independent of the time origin. This means that the auto correlation function of f(t) is the same as that of $f(t - t_o)$ where t_o may have any value.

iv) For real $f(t)$, $R_{ff}(\tau)$ is a real function of τ.

For a case in which the signal $f(t)$ is given as N discrete data points obtained by digitising an analog signal, $f(t_i)$, the auto correlation function may be determined by replacing the integral in equation (2.1) by a summation, such that

$$R_{ff}(\tau) = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} f(t_i)\, f(t_i + \tau) \qquad (2.2)$$

The normalised auto correlation function $R'_{ff}(\tau)$ is defined with respect to deviation from the mean and is given by

$$R'_{ff}(\tau) = \lim_{T\to\infty} \frac{1}{2\sigma_f^2 T} \int_{-T}^{T} [f(t) - \bar{f}][f(t+\tau) - \bar{f}]dt$$

$$= \lim_{N\to\infty} \frac{1}{\sigma_f^2 N} \sum_{i=1}^{N} [f(t_i) - \bar{f}][f(t_i + \tau) - \bar{f}] \qquad \ldots \qquad (2.3)$$

where $\bar{f}$ is the mean value of the time varying signal over one period of a periodic signal or over a discrete number of digitised values of a random signal, and σ_f^2 is the variance of the signal $f(t)$. Strictly speaking, the auto correlation function is computed in the limit of $T\to\infty$ or $N\to\infty$, but in practice, however, a finite amount of data is treated and $R_{ff}(\tau)$ is computed for τ_s upto

$$\tau_{max} \leqslant 0.1\ N$$
$$= M\ \Delta t < N\ \Delta t.$$

For N data points spaced at Δt, such that

$$R'_{ff}(\tau) = \frac{1}{N - \tau/\Delta t} \sum_{i=1}^{N-\tau/\Delta t} [(f_i - \bar{f})(f_{i+\tau/\Delta t} - \bar{f})]/\sigma_f^2 \quad \ldots\ldots (2.4)$$

where

$$\bar{f} = \frac{1}{N} \sum_{i=1}^{N} f_i \text{ and,}$$

$$\sigma_f^2 = \frac{1}{N} \sum_{i=1}^{N} (f_i - \bar{f})^2$$

Substituting $\tau / \Delta t = M$, equation (2.4) can be written as

$$R'_{ff}(\tau) = \frac{1}{N-M} \sum_{i=1}^{N-M} [(f_i - \bar{f})(f_{i} + \frac{\tau}{\Delta t} - \bar{f})]/\sigma_f^2 \quad \ldots (2.5)$$

The auto correlation function $R_{ff}(\tau)$ and the normalised auto correlation function $R'_{ff}(\tau)$ is related by

$$R_{ff}(\tau) = \sigma_f^2 \; R'_{ff}(\tau) + (\bar{f})^2 \quad (2.6)$$

Similarly, cross correlation function $R_{fg}(\tau)$ and normalised cross correlation function $R'_{fg}(\tau)$ for two different signals $f(t)$ and $g(t)$ can be defined by,

$$R_{fg}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t)\, g(t+\tau)\, dt \quad (2.7)$$

and

$$R'_{fg}(\tau) = \lim_{T \to \infty} \frac{1}{2T\, \sigma_f \, \sigma_g} \int_{-T}^{T} [f(t) - \bar{f}][g(t+\tau) - \bar{g}]dt \quad \ldots\ldots (2.8)$$

For N data points spaced Δt apart the normalised cross correlation function may be written for upto $\tau_m = M\,\Delta t < N\,\Delta t$ as,

$$R'_{fg}(\tau) = \frac{1}{(N - \frac{\tau}{\Delta t})} \sum_{i=1}^{N-\frac{\tau}{\Delta t}} \left[(f_i - \bar{f})(g_{i+\frac{\tau}{\Delta t}} - \bar{g})\right] / \sigma_f \cdot \sigma_g \quad \ldots \quad (2.9)$$

where

$$\bar{f} = \frac{1}{N} \sum_{i=1}^{N} f_i$$

$$\bar{g} = \frac{1}{N} \sum_{i=1}^{N} g_i$$

$$\sigma_f^2 = \frac{1}{N} \sum_{i=1}^{N} (f_i - \bar{f})^2$$

$$\sigma_g^2 = \frac{1}{N} \sum_{i=1}^{N} (g_i - \bar{g})^2$$

The cross correlation function represents the degree of confirmity between two signals and it is useful in describing a system's response in the time domain.

2.3 POWER SPECTRAL DENSITY FUNCTION:

Measurements of power spectral density function of physical data establish [24] the frequency composition of the data which, in turn, bears important relationship to the basic characteristics of the system involved.

Wiener Theorem [24] for auto correlation states that auto correlation function of a stationary random signal and the power spectral density are related to each other by a fourier cosine transformation as given by,

$$R_{ff}(\tau) = \int_{-\infty}^{\infty} \phi(f)\, e^{i\omega\tau}\, df \quad , \; \omega = 2\pi f$$

$$= 2 \int_{0}^{\infty} \phi(f) \cos\omega\tau \; df \qquad (2.10)$$

where $\phi(f)$ is power spectral density and is given by,

$$\phi(f) = \lim_{\tau_m \to \infty} \int_{-\tau_m}^{\tau_m} R_{ff}(\tau)\, e^{-i\omega\tau}\, d\tau$$

$$= \lim_{\tau_m \to \infty} 2 \int_{0}^{\tau_m} R_{ff}(\tau) \cos\omega\tau \; d\tau \qquad (2.11)$$

With N discrete values of $R_{ff}(\tau)$ spaced Δt apart, the power spectral density [22] can be expressed as,

$$\phi(f) = \frac{2}{N} R_{ff}(0) + \frac{2}{N} \sum_{j=1}^{M} R_{ff}(j\,\Delta t) \cos 2\pi f_j\, \Delta t$$

$$= 2\Delta t\, R_{ff}(0) + 2\Delta t \sum_{j=1}^{M} R_{ff}(j\Delta t) \cos 2\pi f_j \Delta t$$

$$\ldots \qquad (2.12)$$

CHAPTER - III

EXPERIMENTAL DETAILS

3.1 INTRODUCTION:

Experiments are carried out under plunge cut grinding conditions on a horizontal surface grinding machine. Radial and tangential vibration signals are analysed for auto correlation function and power spectral density functions. The wheel wear, wheel loading and workpiece roughness are measured to establish any correlation with the characteristics of the vibration signals.

3.2 TRUING AND DRESSING TECHNIQUE:

Dressing conditions affect grinding performance[19] significantly. In order to obtain reproducible results, wheel dressing is standardised in term of down feed and cross feed rate of the wheel. The grinding wheel used was subjected to the following truing and dressing conditions:

(i) All traces of loaded material and irregularities of previous grinding operations are removed by truing at a depth of cut 1o micron during each pass.

(ii) Truing operation is terminated after giving 10 spark out passes.

The dressing operation is performed with a single point diamond dresser inclined at an angle of 13 degrees with the vertical along the direction of wheel motion. After truing the wheel is dressed by giving a single pass of 6 micron dressing depth of cut at a cross feed rate of 2 m/min.

Grinding wheel is properly balanced before dressing on a roll-stand.

3.3 DEBRIS COLLECTION AND SEPARATION OF ABRASIVE GRAINS:

Debris composed of mild steel particles and abrasive grains, generated during grinding process, are collected in a box enclosing the grinding zone. The inside walls of the collector box are coated with white petrolatum grease which catch the abrasive and mild steel particles. The grease and debris is scraped from the box. The abrasive and mild steel particles are separated from grease by washing it in benzene. Mild steel and abrasive particles are put in aqua regia. Most of the mild steel particles are dissolved in aqua regia. Abrasive particles are separated by filtering and dried. Remaining metallic particles, if any, are removed with the help of a magnet. The abrasive particles are weighed on an electronic balance. This weight of abrasive particles is the value of wheel wear. Similar technique is used for evaluation of loading of the wheel.

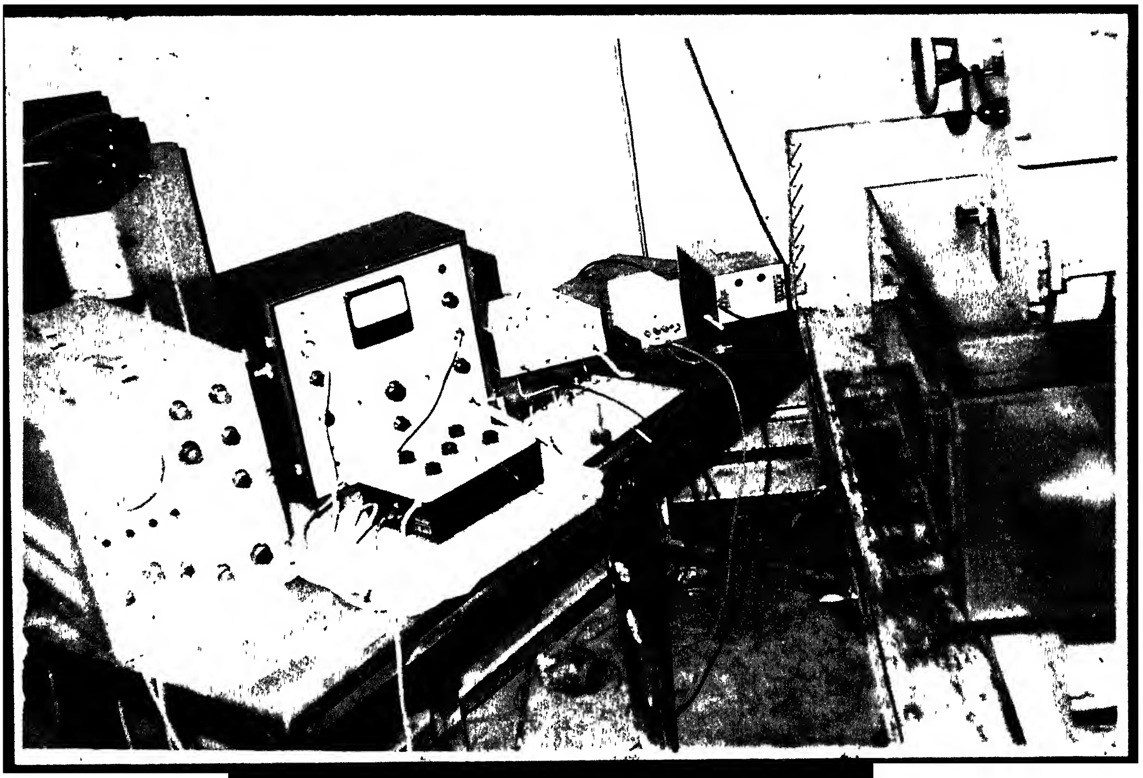


Fig. 1 Experimental set-up

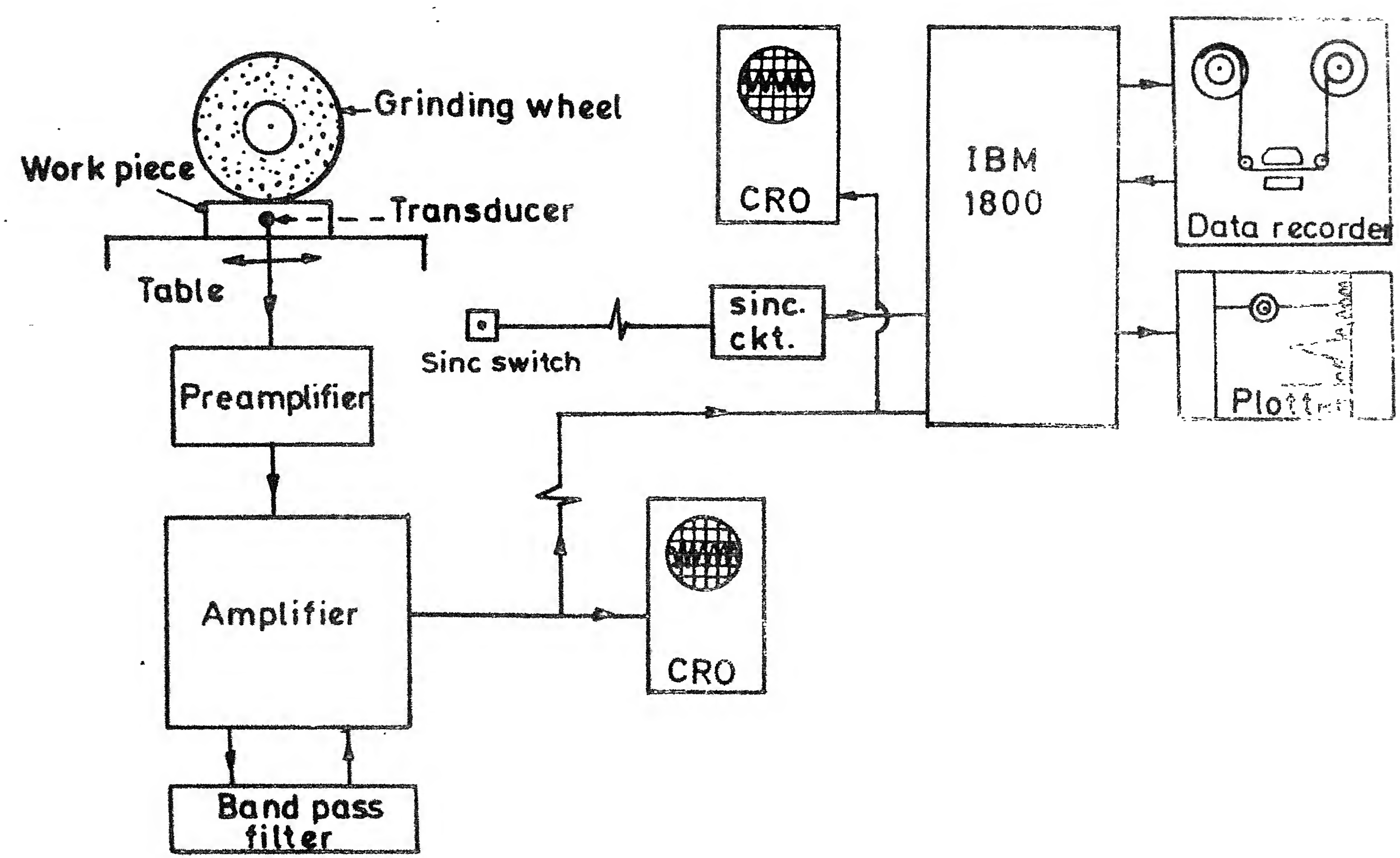


FIG.2 TEST SETUP FOR VIBRATION SIGNAL RECORDING

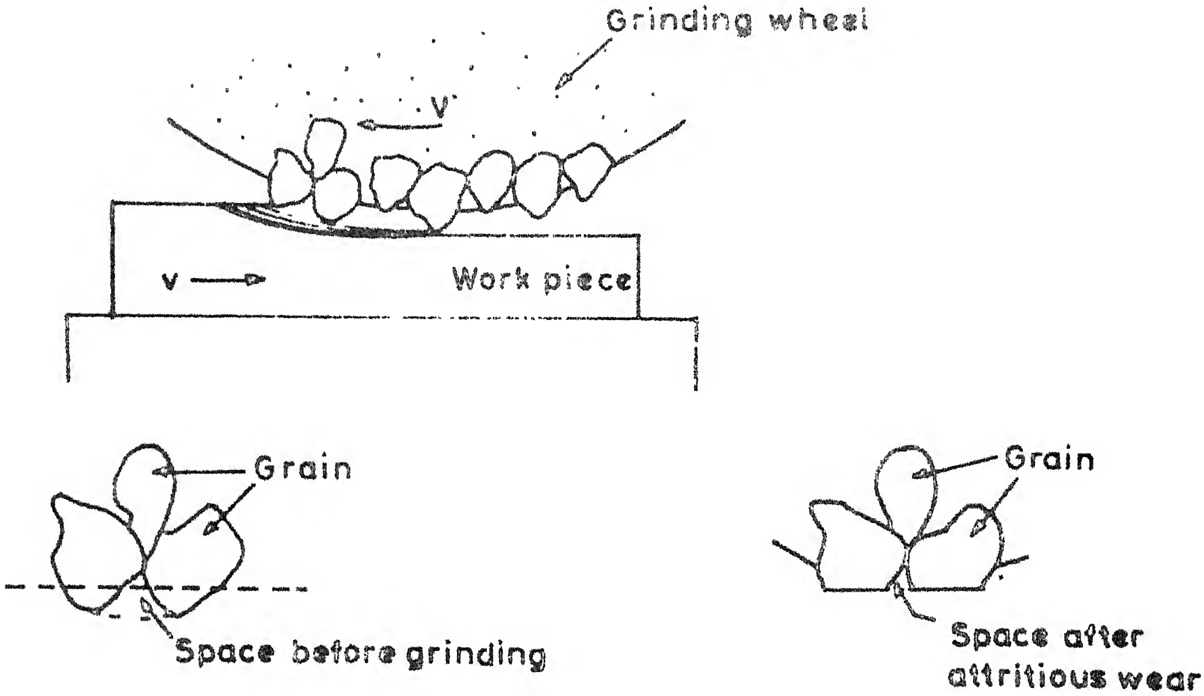
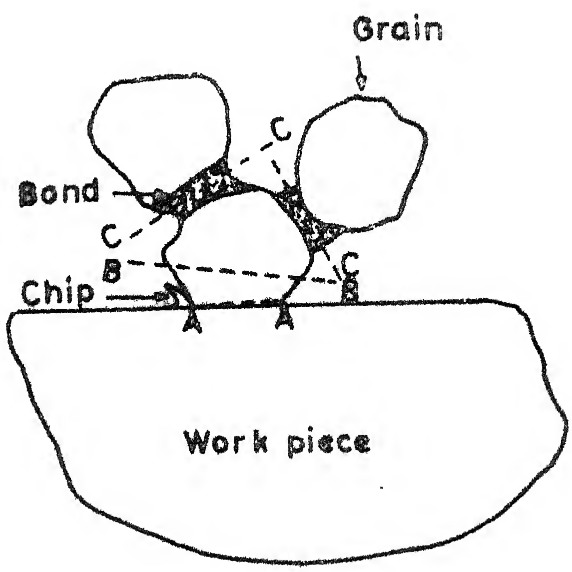


FIG 3 A ATTRITIOUS WEAR AND LOADING



FIG·3B ILLUSTRATION OF THREE TYPES OF WEAR

AA – Attritious wear ; BB-Grain fracture
CC – Bond fracture

3.4 SIGNAL RECORDING TECHNIQUE:

Vibration signals produced by grinding are in analog form. For recording the vibration signal in the computer, first the analog signal is converted into digitised form by the analog to digital converter (ADC) and then stored in the magnetic tape. The magnetic tape is first initialised through computer program and then logging program is executed. When the computer is ready for logging the signal, proceed light comes on the keyboard of the typewriter and a header location is given to computer to distinguish the signal. Then a message is given to the grinding operator to send the signal. During grinding, the vibration signals are generated at each pass. For recording a particular signal, a sinc. pulse of -12 volt is needed. For generating sinc. pulse, a special circuit is designed. When the sinc. pulse comes, the computer records the vibration signal. This processing of the signal takes about 15 sec. After this interval, the computer is again ready to accept another signal and proceed light comes for recording the next signal.

After recording the signal, computer program is executed for calculating auto-correlation coefficient and power spectral density.

3.5 EXPERIMENTAL CONDITIONS:

Plunge cut grinding test are done on mild steel specimen. The experiments are conducted on type SFW-1, model no. 1138, horizontal surface grinding machine manufactured by Hindustan Machine Tool Ltd., Bangalore.

The grinding wheel, A36-J5-V10, supplied by M/s Carborundum Universal Ltd., Madras, is used. The diameter, width and bore of the wheel are :272 mm, 63 mm, 76 mm respectively.

The following experimental conditions are employed in the present work:

Wheel speed (V)	:	1500 r.p.m.
Depth of cut (D)	:	6 micron.
Table speed (v)	:	15 m/min.
Workpiece material	:	Mild steel (60 RB)
Workpiece dimensions	:	220 mm X 51 mm X 78 mm
Length of stroke	:	700 mm
Grinding fluid	:	Dry
Dressing conditions	:	Described in 3.2

All tests are run under plunge cut condition such that the width of the wheel is greater than the width of the workpiece.

The complete experimental set-up is shown in Fig. 1.

3.6 EXPERIMENTAL SET-UP FOR SIGNAL RECORDING:

The schematic view of the test set-up for vibration signal recording is shown in Fig. 2. Radial and tangential vibrations during the surface grinding process are measured. Piezoelectric type of transducer (B-K Accelerometer type 4334) is used to monitor the vibration signal.

The transducer is suitably mounted with the help of a magnetic base on the test piece to sense vibrations of maximum amplitude. The signal is first pre-amplified by a pre-amplifier (B-K Pre-amplifier type 1606). Then the signal is amplified by a two-stage amplifier (B-K Microphone amplifier type 2603). The signal is first amplified (in 1st stage) and then filtered by passing it through a band pass filter (K-H Model 3700) having wide frequency range of 0.2 Hz to 20,000 Hz. The lower cut-off frequency (200 Hz) is chosen so as to filter the noise from the various sources in the system. The higher cut off frequency is chosen as 4.5 KHz. Both, the lower cut-off and higher cut-off frequencies are decided on the basis of preliminary grinding tests and natural frequency of the machine tool. Finally the filtered signal is amplified by the second stage of the amplifier and recorded on the magnetic tape of the computer (IBM-1800).

The IBM 1800 is a process computer which has the facilities for online data logging and computation of the signal.

3.7 PROCEDURE:

The grinding wheel is brought close to the workpiece. The table speed is set at the desire value and then the wheel is started. The desired depth of cut is given during each stroke. After specific number of passes, the machine is stopped. The roughness of the workpiece is measured by a profilometer (Micrometrical Manufacturing Co., USA). The debris along with the grease is scrapped from the inner wall of the box for calculating wheel wear. The loaded metallic particles in the wheel are dislodged from the wheel by a diamond dresser. This is also collected in a box like container with the help of grease. The wheel is dressed for next set-up. Again grease is applied in the inner wall of the box and the grinding is continued untill the wheel needs redressing. Redressing point is assumed to have reached when grinding burns appear on the work surface.

Wheel wear, wheel loading and workpiece roughness are calculated for both up grinding and down grinding conditions for different number of passes.

Before starting the experiment for recording the vibration signal, electronic instruments (Fig. 2) are allowed to warm up for 15 minutes both in shop floor and computer centre. Necessary computer program are executed for storing the digitised data of the vibration signal. When the computer is ready for logging the signal, the grinding operation is started. After intervals of 25 passes, vibration signals are recorded on the magnetic tape of the computer. Both tangential and radial vibration signals are recorded for up grinding and down grinding conditions. The process is continued untill it become apparent that the wheel needs dressing.

The recorded signals are analysed for plotting auto correlation function and power spectral density as explained in the next section.

3.8 SIGNAL PROCESSING:

For finding out the smooth power spectrum, it is necessary to decide [24] digitization rate, number of samples, number of correlation points and window for smoothening the raw spectrum. The process of digitizing consists of converting continuous data into discrete numbers. These involve two main parts, one is sampling and other is quantization. The sampling is defined as selection of the points at which the data are observed. If the sampled values are

separated too far apart, sampled values would represent either too low or too high frequencies in the original data. If it is too small, then sampling yields correlated and highly redundant data.

The digitization rate is given by the sampling theorem as

$$\Delta t = \text{digitising interval} = \frac{1}{2f_N}$$

$$\text{or} \quad f_N = \frac{1}{2\Delta t} = \frac{N}{2T}$$

In some cases, frequencies higher than f_N may appear in the power spectrum and may not be distinguishable from the lower frequencies. To overcome this problem, the resolution rate is chosen such that:

$$\Delta t = \frac{1}{2f_{max}}$$

where f_{max} is the maximum possible frequency of interest in the investigation.

In standard practice the number of auto correlation points M are taken in between 5 to 15% of N.

The raw power spectrum from the auto-correlation signal needs to be smoothed by using windows in order to eliminate all the unwanted irregularities.

The frequently used windows are,

(i) $0.5 + 0.5 \cos \frac{\pi\tau}{\tau_m}$ Hanning window

(ii) $0.54 + 0.46 \cos \frac{\pi\tau}{\tau_m}$ Hamming window

(iii) $$\left.\begin{array}{ll} (1 - \frac{\tau}{\tau_m})(1 - 6\frac{\tau}{\tau_m})^2 & \tau < \frac{\tau_m}{2} \\ 2(1 - \frac{\tau}{\tau_m})^3 & \tau > \frac{\tau_m}{2} \end{array}\right\}$$ Parzen window.

In the present work, power spectral density and the smoothed power spectral density are calculated by using the following expressions, given by Parzen [22]

$$\emptyset (f) = 2 \Delta t \; R_{ff}(0) + 2 \Delta t \sum_{j=1}^{M} R_{ff}(j \Delta t) \cos 2\pi f_j \Delta t \qquad \ldots \qquad (3.1)$$

$$\emptyset'(f) = 0.25 \, \emptyset \left(f - \frac{1}{2}\tau_m\right) + 0.50 \, \emptyset (f) + 0.25 \, \emptyset\left(f + \frac{1}{2\tau_m}\right) \qquad \ldots \qquad (3.2)$$

In the present work 16 bit analog to digital converter is chosen for higher accuracy. Each signal is digitised into 1000 samples. For calculating auto-correlation function 300 samples are used. Maximum number of auto-correlation points, M, are taken 40 for calculating auto-correlation function and power spectral density.

CHAPTER - IV

RESULTS AND DISCUSSIONS

4.1 WHEEL WEAR:

Figure 16 shows the variation of wheel wear with number of passes for both up and down grinding conditions. Three regions of the wear characteristic curve are clearly distinguished.

Initially there is a rapid increase in wheel wear upto 25 passes, wheel wear increases at a slower rate upto about 150 passes and shows a steep rise thereafter for up grinding. It is seen that wheel wear in down grinding is slightly more than that in up grinding. The experimental results show that the redressing needs to be done after 125-150 passes for the grinding condition described earlier.

4.2 WHEEL LOADING:

Figure 17 shows the variation of wheel loading with number of passes. In the early stages of grinding (for 25 passes) wheel gets heavily loaded. The loading decreases with further increase in the number of passes showing a minimum value between 50 and 75 passes. The

wheel loading increases upto 125 passes and reaches a steady value where burning is observed.

In the initial stage when the wheel is in redressed condition, larger space between the grains is available for the metal particles as shown in Fig. 3A. With further grinding, attritious wear takes place and the grains become blunt leaving lesser space between the grains causing drop in the loading curve (Fig. 17). As the grinding proceeds the forces on the grains increase resulting in partial fracture and finally bond post fracture. This presents new grains for the grinding action and is responsible for increase in loading till a condition of burning is observed in the range of 125-175 passes necessitating redressing.

4.3 SURFACE ROUGHNESS:

Figure 18 shows the variation of surface roughness with number of passes. It is seen that as the number of passes increase, the surface roughness increases upto 100 passes for up grinding and then drops to a steady value at about 150 passes. Similar variation can be seen in the case of down grinding also.

Due to increased loading at 125 passes (Fig. 17) the burnishing action of the blunt grains causes a smoother surface.

Burning is observed after 125 passes for down grinding and at about 175 passes for up grinding suggesting redressing of the wheel.

4.4 RANDOM VIBRATION ANALYSIS:

Figures 4, 5, 6 and 7 show the tangential and radial vibration plots for up and down grinding conditions.

Figure 8, 9, 10 and 11 show the typical auto correlation plots for different grinding conditions. It is seen that the amplitude of auto correlation function is maximum for zero delay time and the amplitude of auto correlation function changes periodically with increase in delay time.

Figures 12, 13, 14 and 15 show the typical power spectral density plot for different grinding conditions. It is seen that the peak of the power spectral density occur at different frequencies.

Figures 23, 24 and 25 show the variation of frequency fp corresponding to peak power spectral density with number of passes for radial and tangential vibration in the case of up grinding and down grinding conditions.

Figures 19, 20, 21 and 22 show the variation of peak power spectral density with number of passes for

radial and tangential vibration in the case of up grinding and down grinding conditions.

For radial vibration in up grinding (Fig. 19) the power spectral density shows a steep rise at about 125 passes. This steep rise in power spectral density for tangential vibration is also observed at about 100-125 passes. The steep rise corresponds to the suggested redressing condition of the wheel as observed in Figures 16 and 17, characterising wear and loading.

However no such correlation between loading and wear of the wheel and power spectral density in down grinding (Figures 16, 17, 21 and 22) is observed.

CHAPTER - V

CONCLUSIONS AND FUTURE WORK

While grinding Mild Steel with A36-J5-V10 wheel for specific up grinding conditions of the test, there is a steep rise in the power spectral density after 125 passes. After about the same grinding time, there is a significant change in wheel wear and wheel loading for the same grinding conditions.

Redressing point in the range of 125-150 passes, as observed from the wheel loading and wheel wear tests, is also predicted from the steep rise in power spectral density in up grinding. From the results of the present investigation, it is concluded that wheel loading has significant effect on power spectral density of the random vibration signals during up grinding.

For future work, it is suggested that the random analysis could be carried out for a range of table speeds, depth of cut and different type of grinding wheels employing the system used in this investigation. This would eventually lead to automatic control of redressing the grinding wheel by monitoring the random vibration signal.

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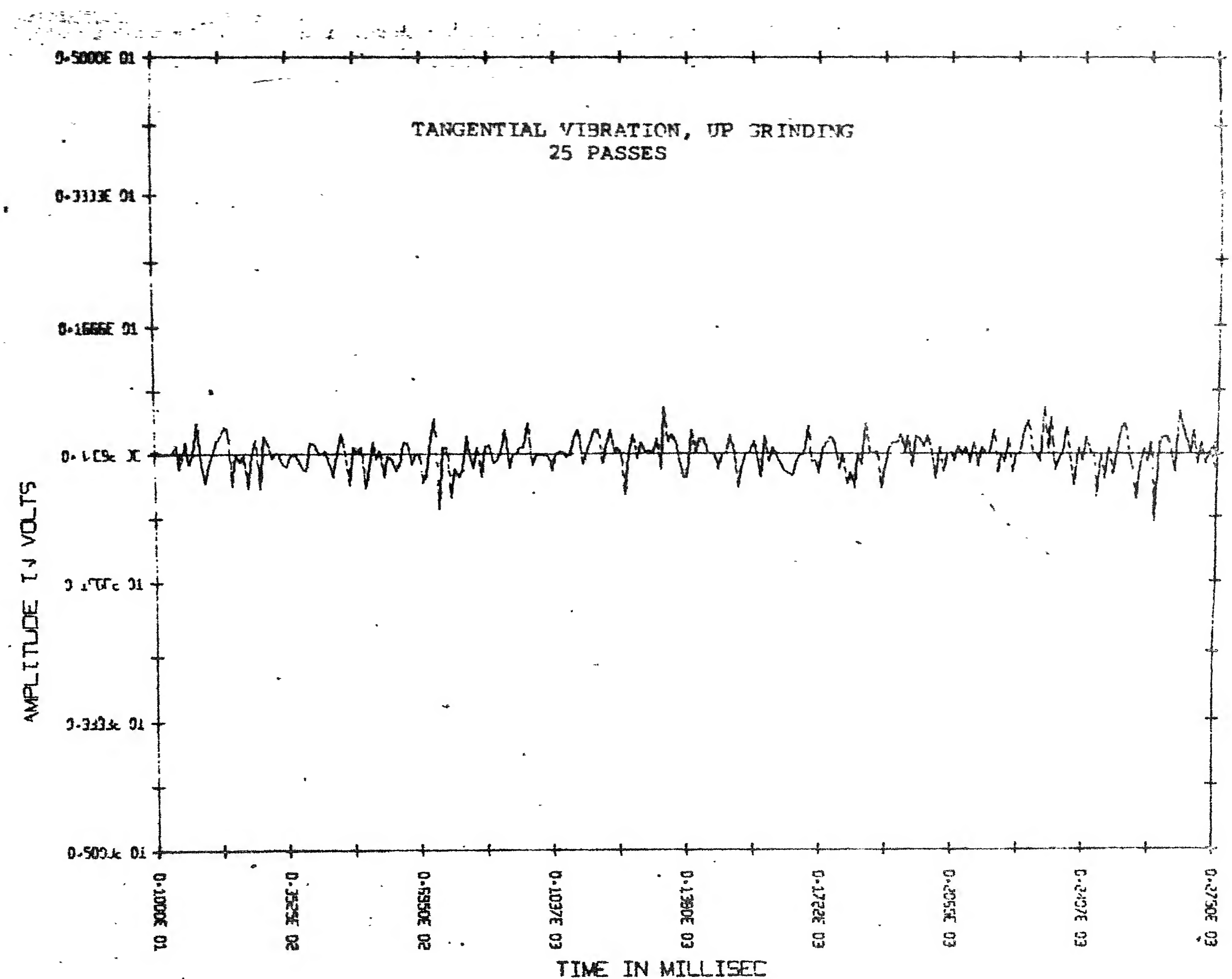


FIG. 4 VIBRATIONAL PLOT

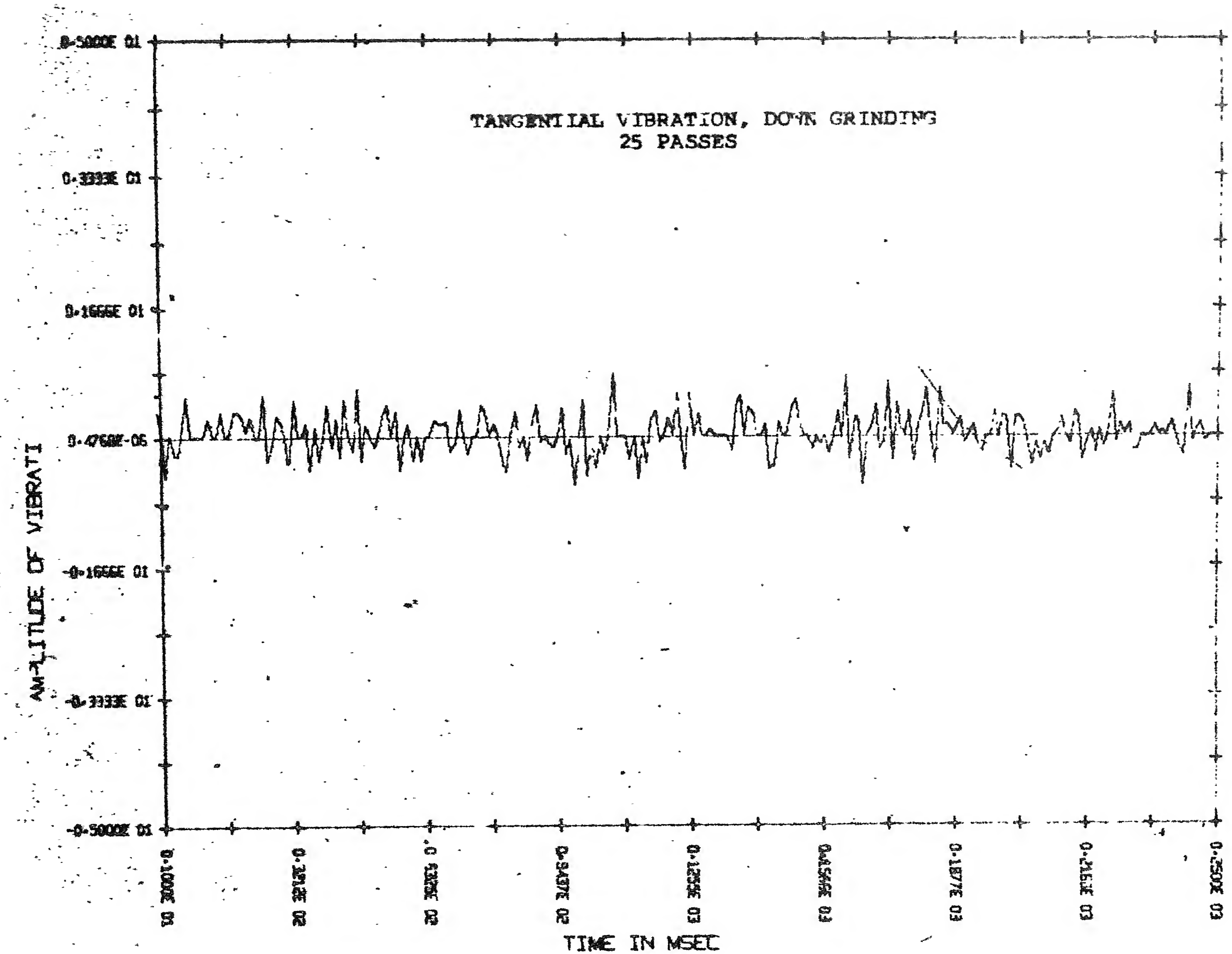


FIG. 5 VIBRATIONAL PLOT DOWN GRINDING

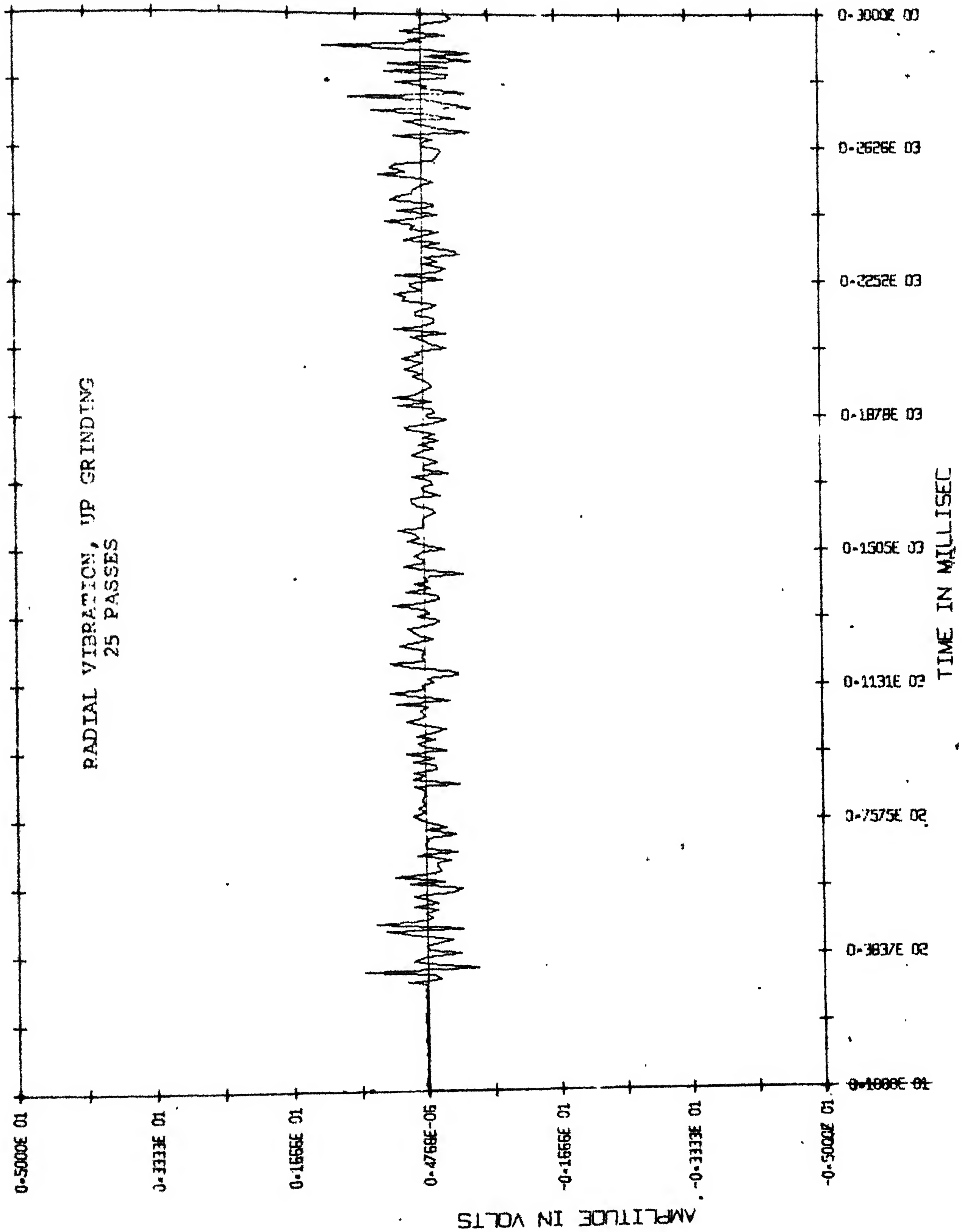


FIG. 6 VIBRATIONAL PLOT

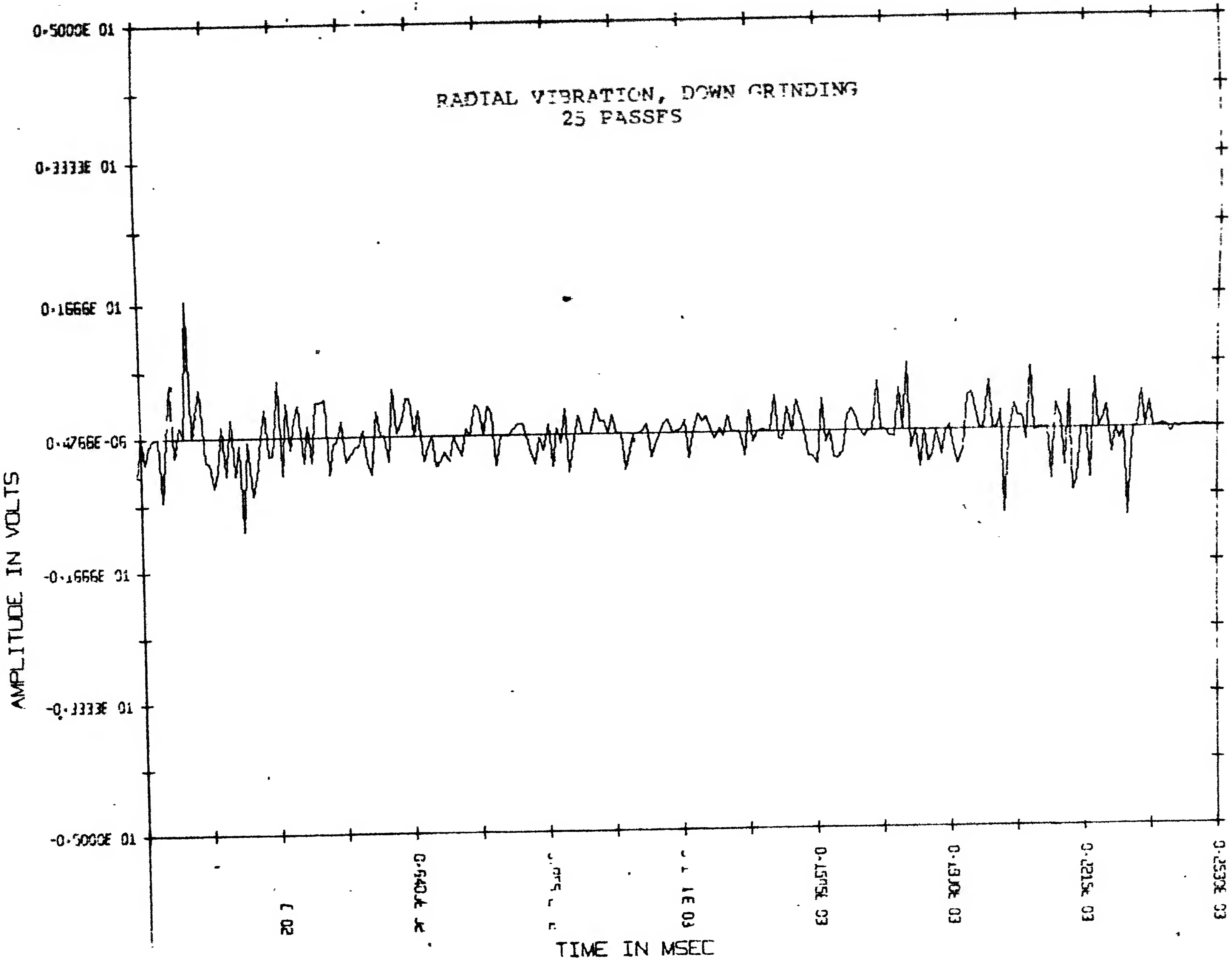


FIG.7 VIBRATIONAL PLOT

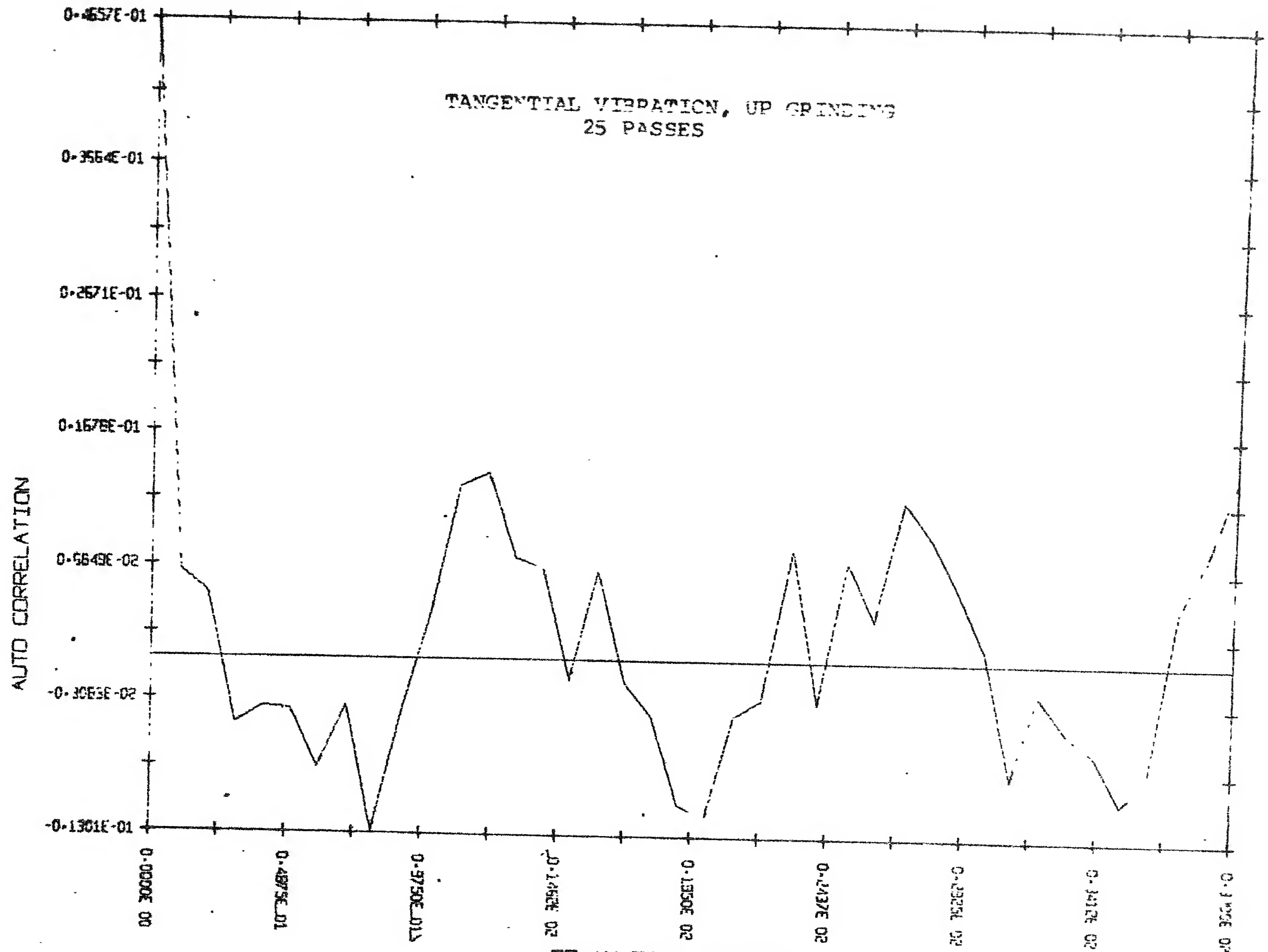


FIG. 8 AUTO CORRELATION PLOT

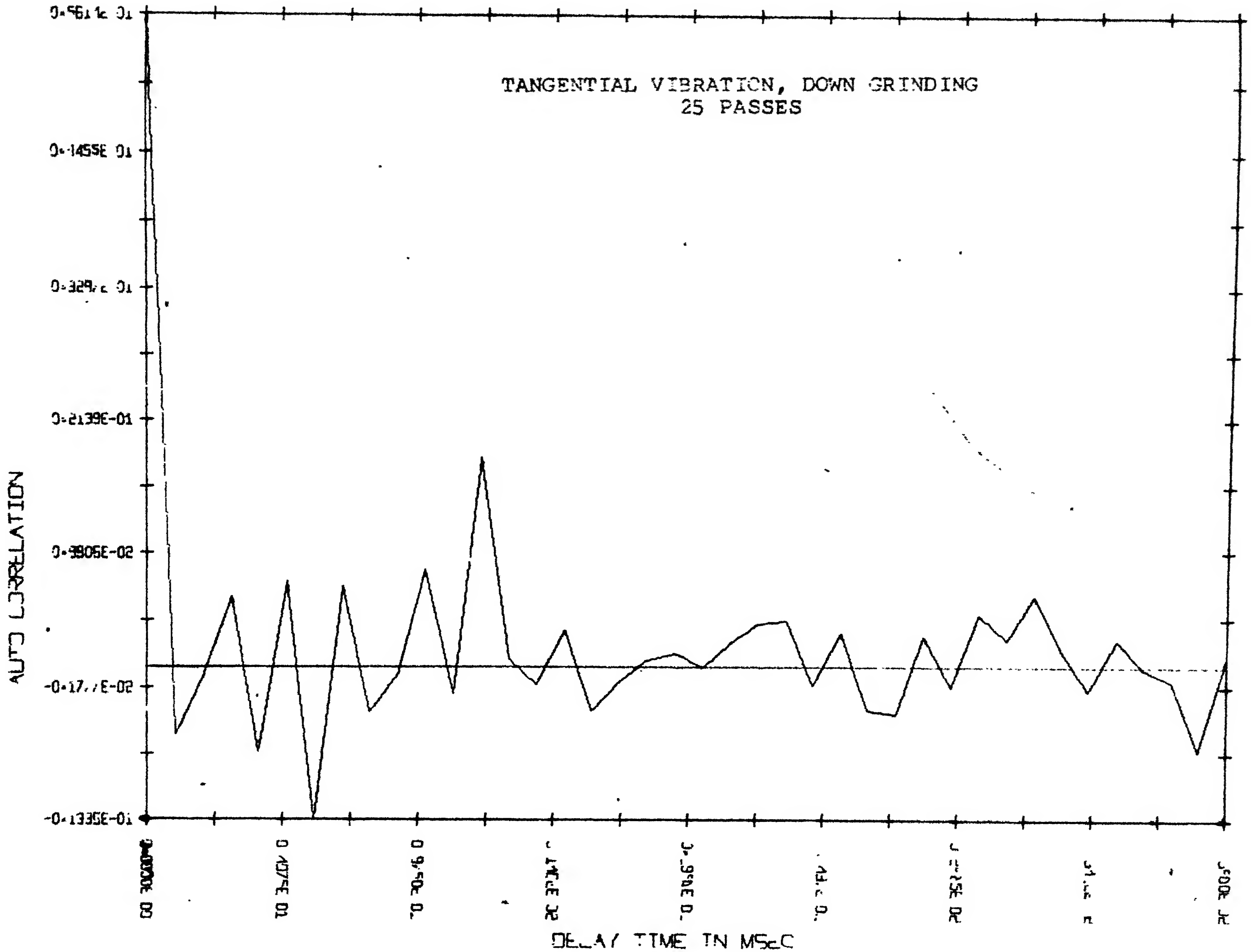


FIG. 9 AUTO CORRELATION PLOT

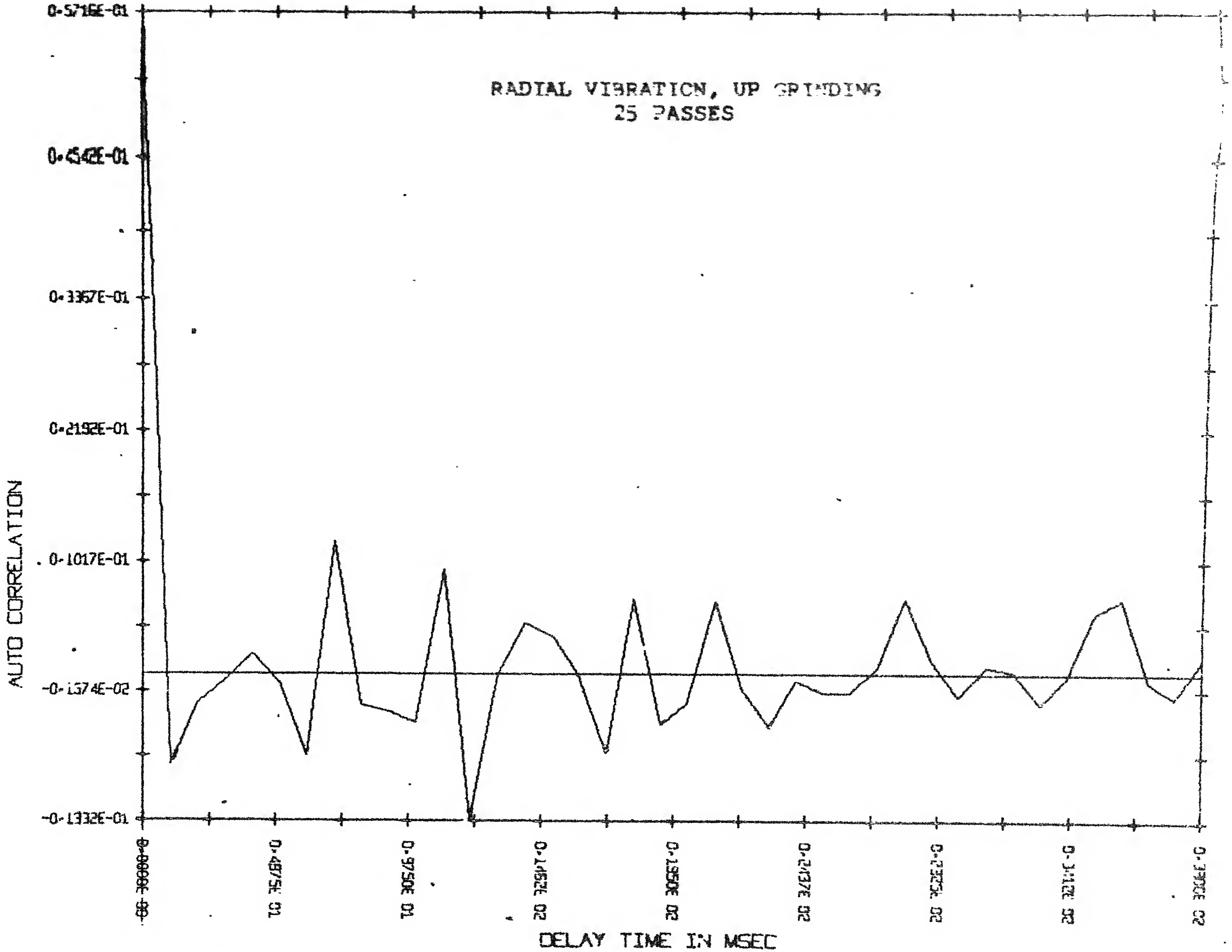


FIG. 10 AUTO CORRELATION PLOT

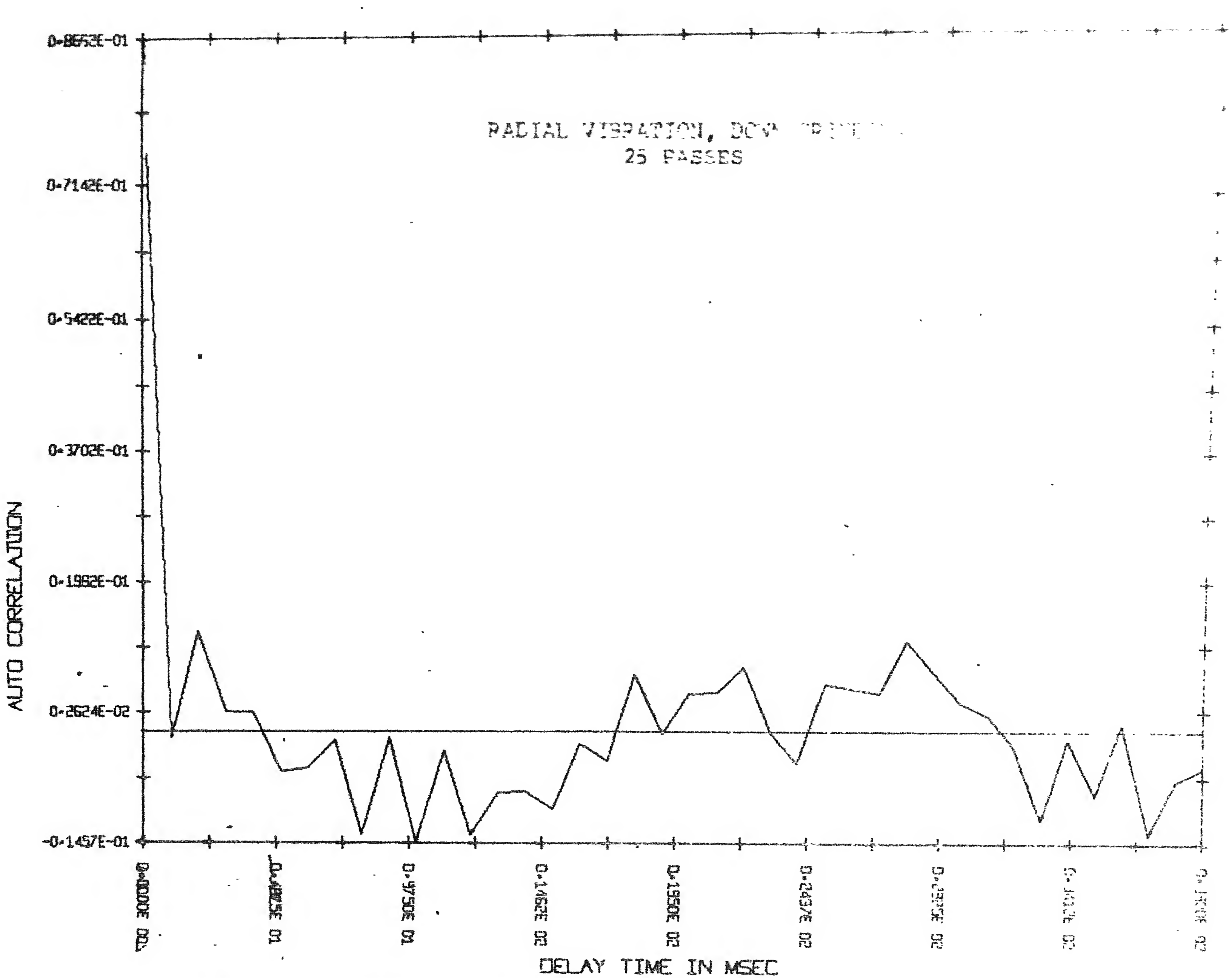
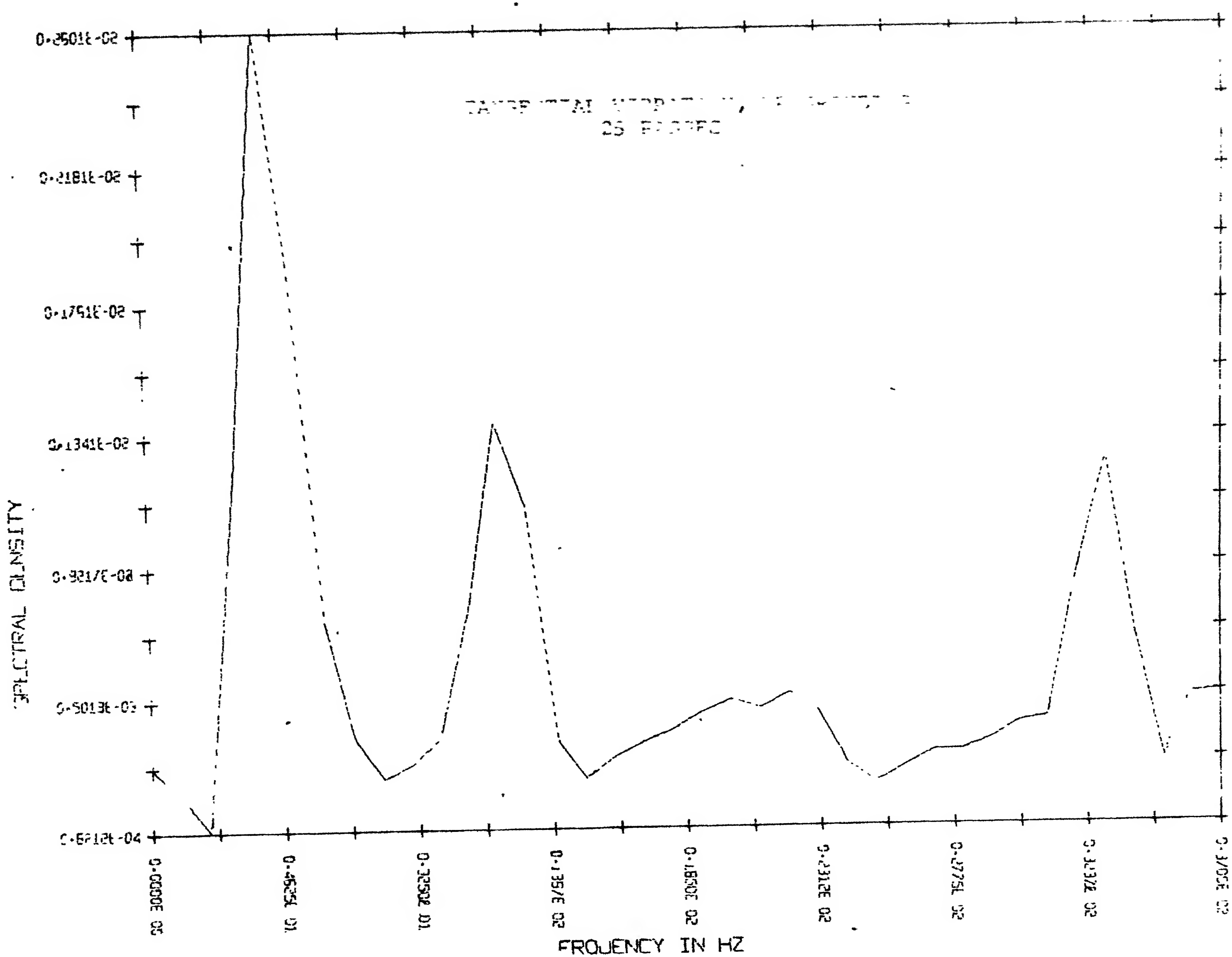


FIG. 11 AUTO CORRELATION PLOT



FIG·12 SMOOTHED SPECTRAL DENSITY PLOT

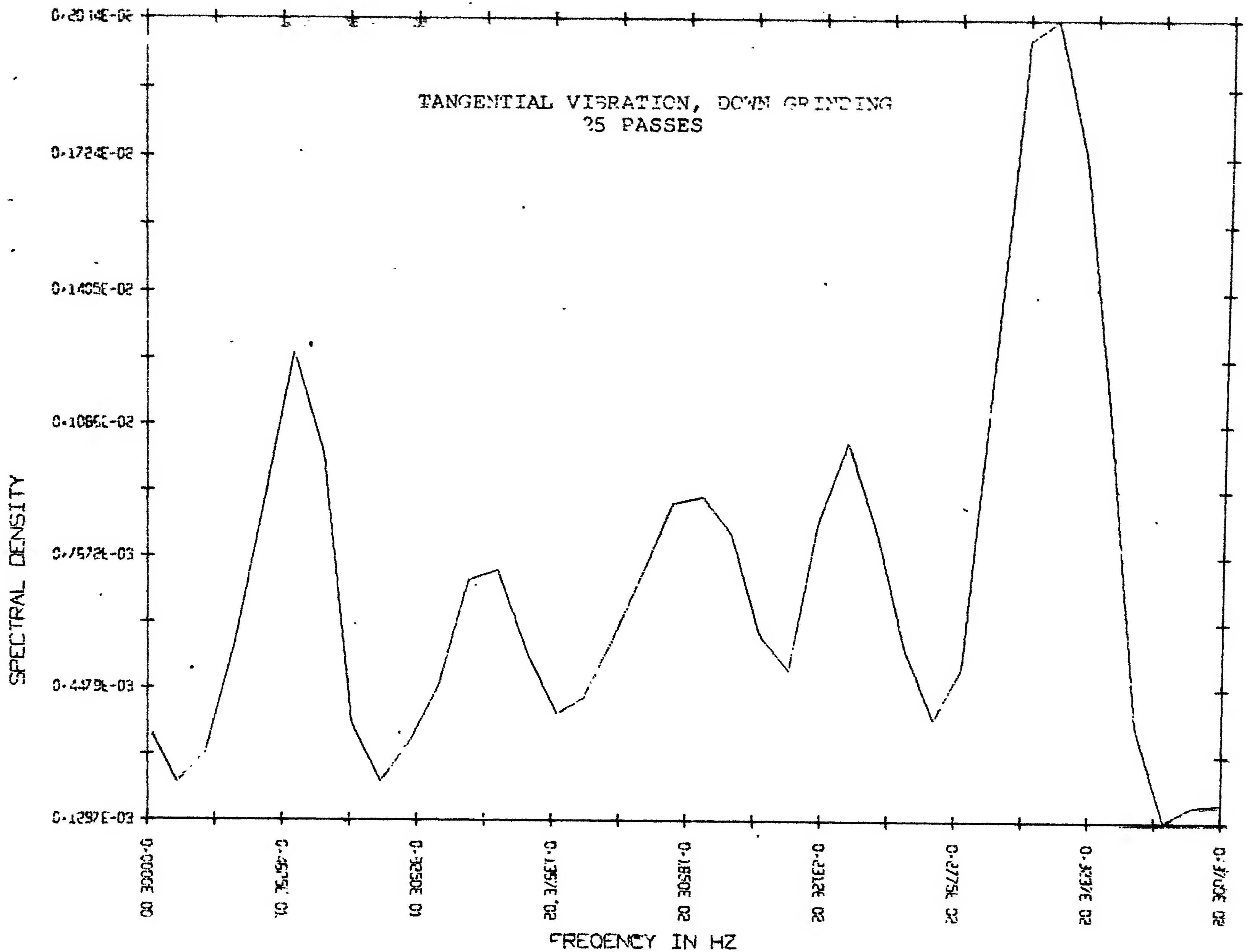


FIG. 13 SMOOTHED POWERSPECTRAL DENSITY PLOT

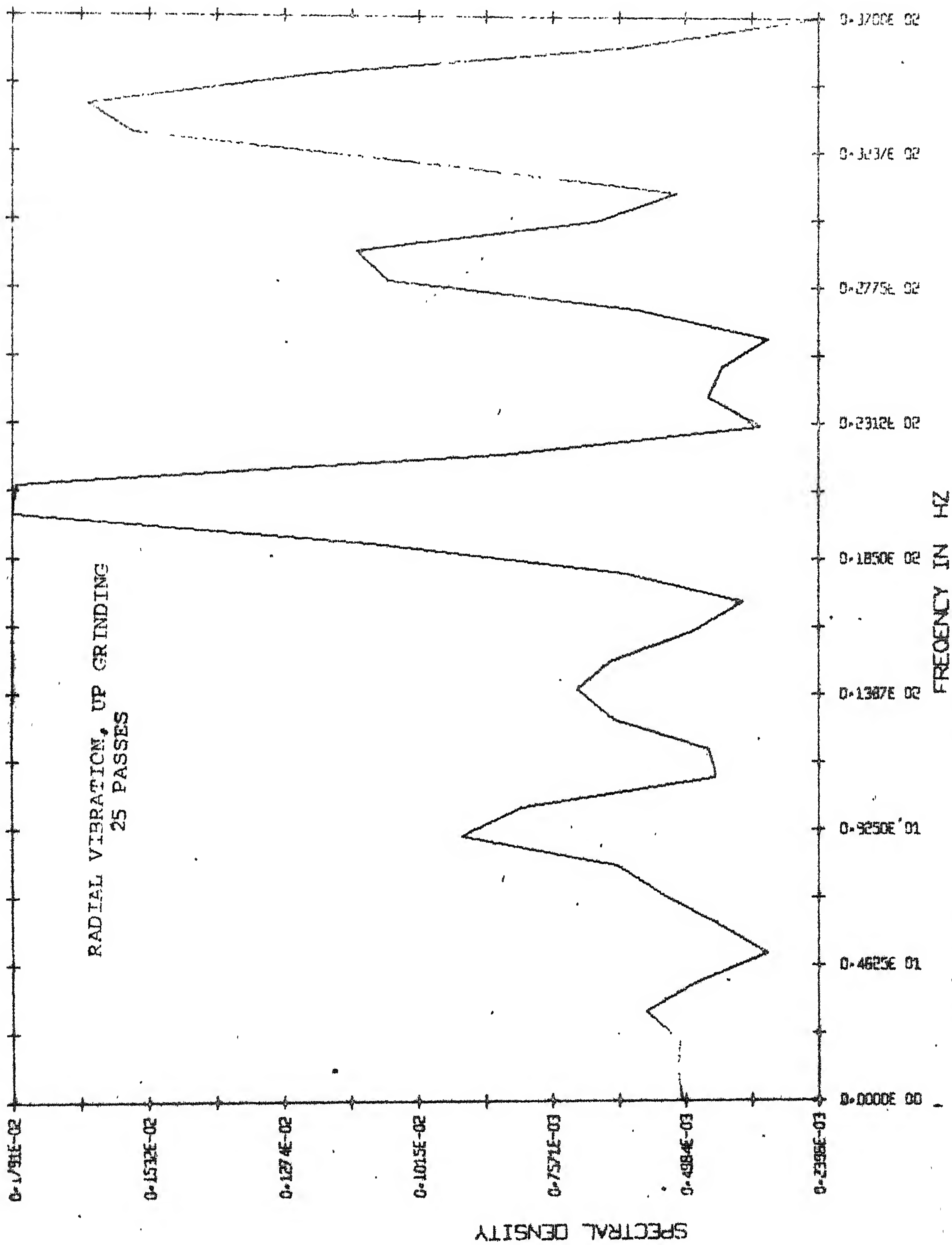


FIG. 14 SMOOTHED SPECTRAL DENSITY PLOT

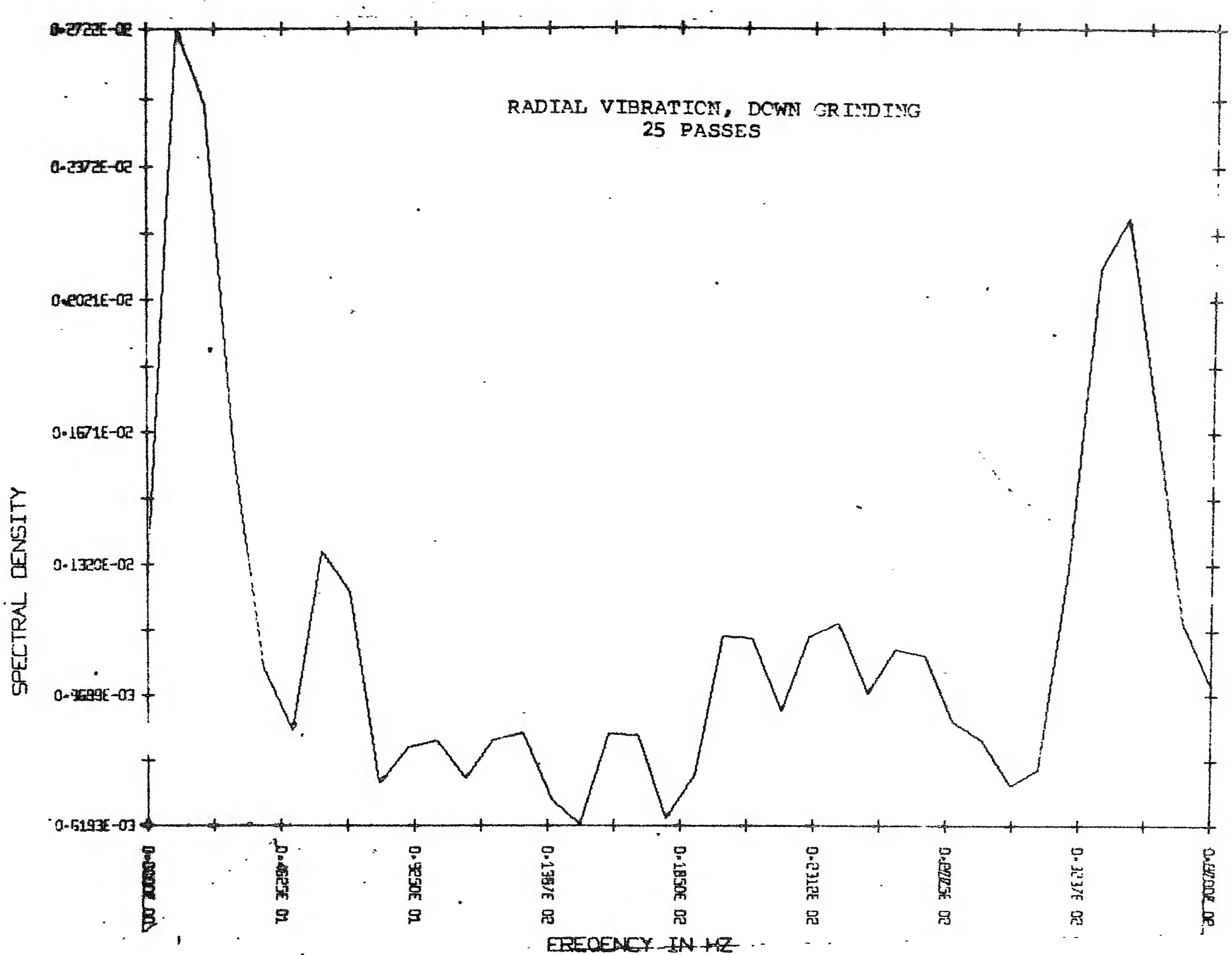


FIG.15 SMOOTHED SPECTRAL DENSITY PLOT

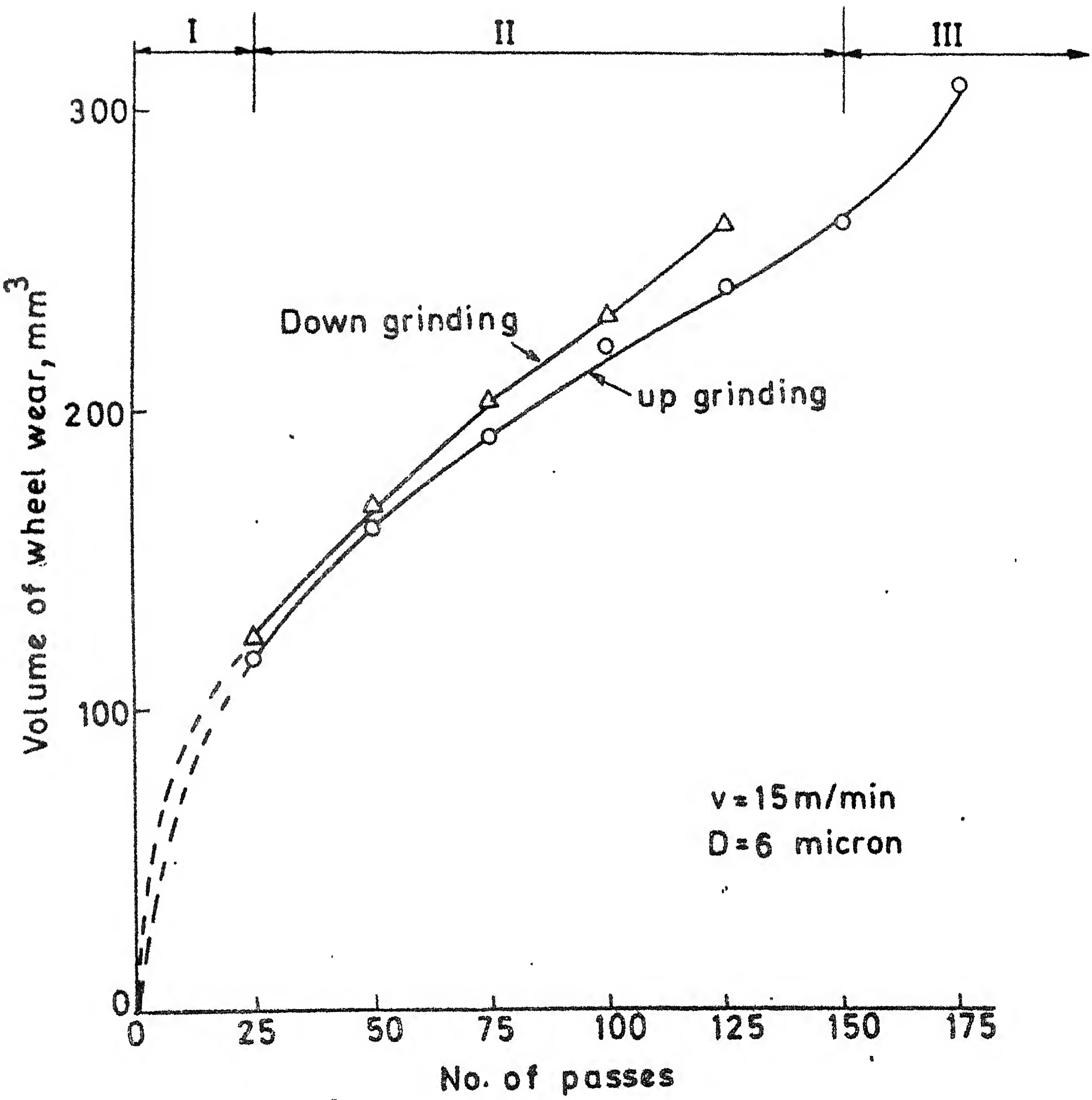


FIG.16 VARIATION OF WHEEL WEAR WITH NO. OF PASSES

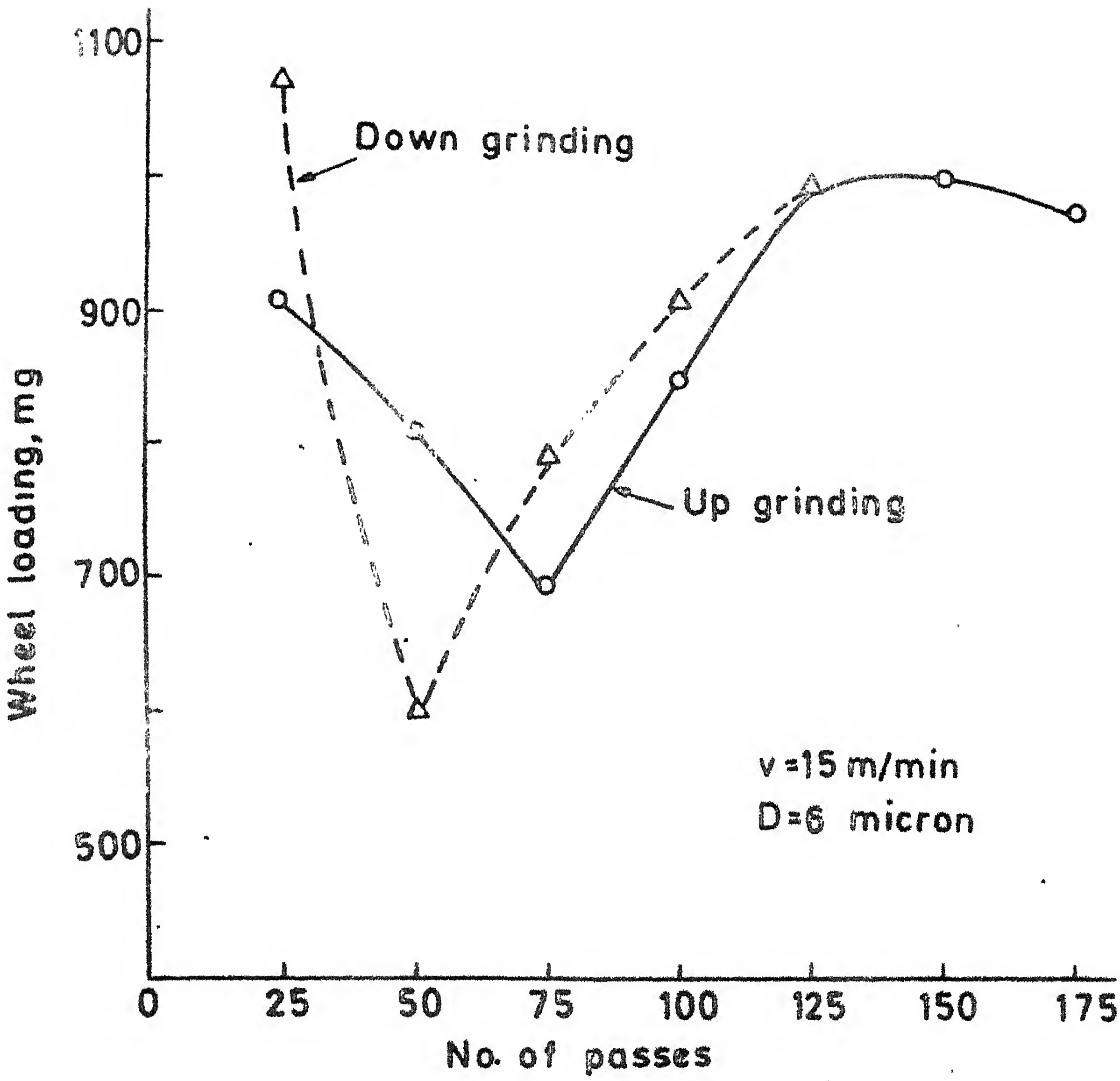


FIG.17 VARIATION OF WHEEL LOADING WITH NO. OF PASSES.

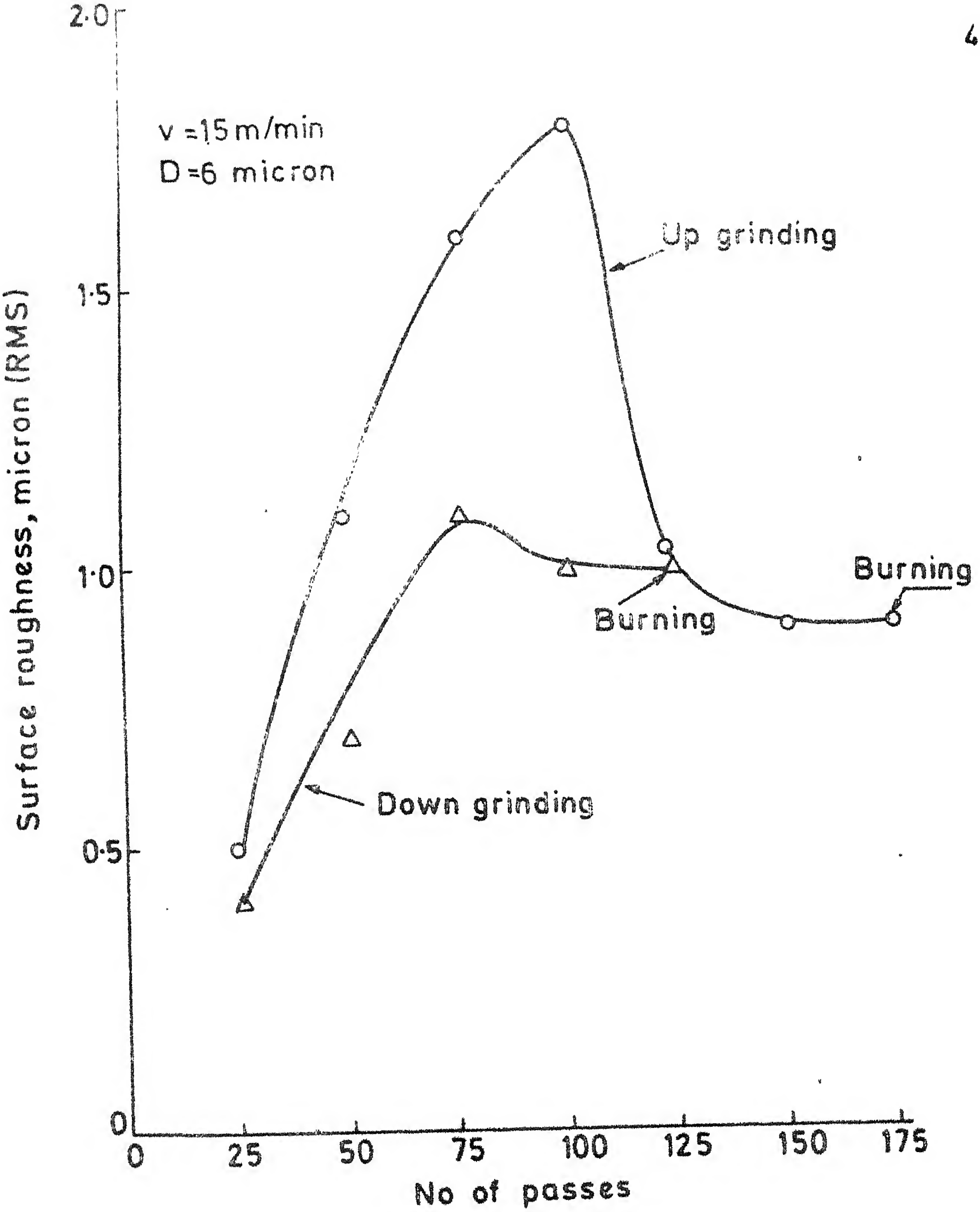


FIG.18 VARIATION OF WORK PIECE ROUGHNESS WITH NO. OF PASSES

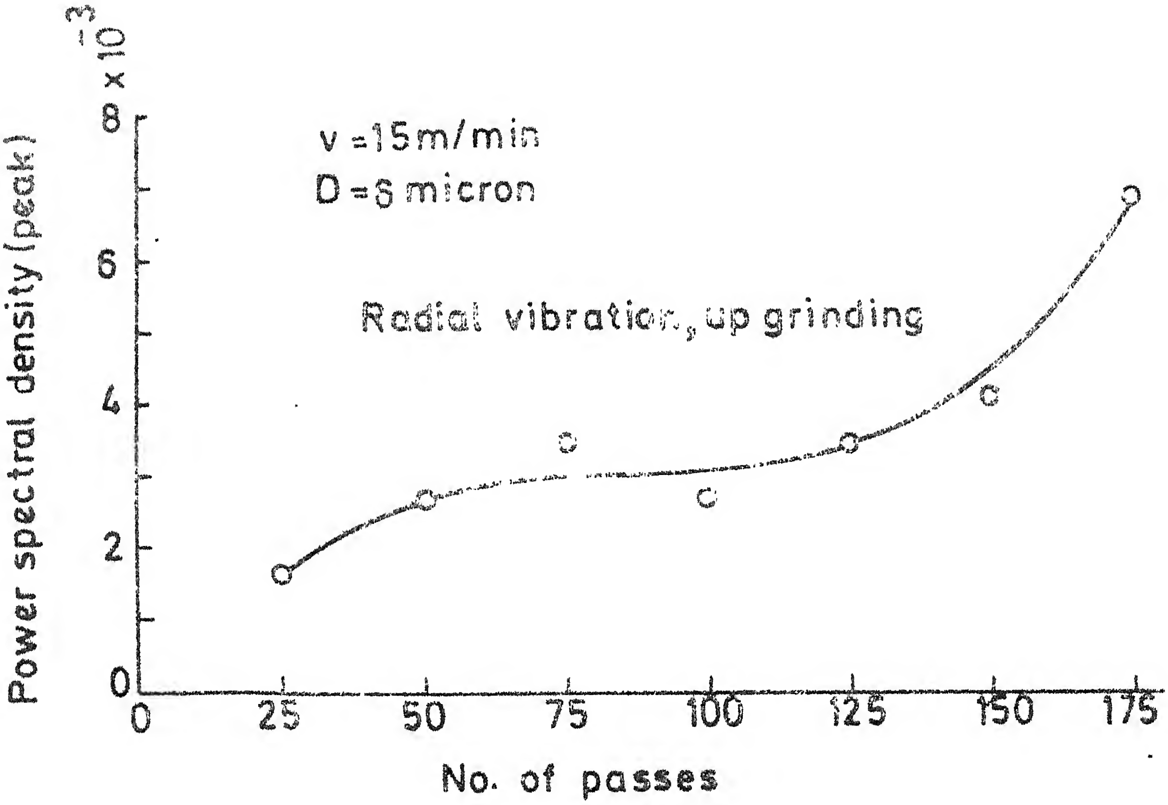


FIG.19 VARIATION OF PSD WITH NO. OF PASSES

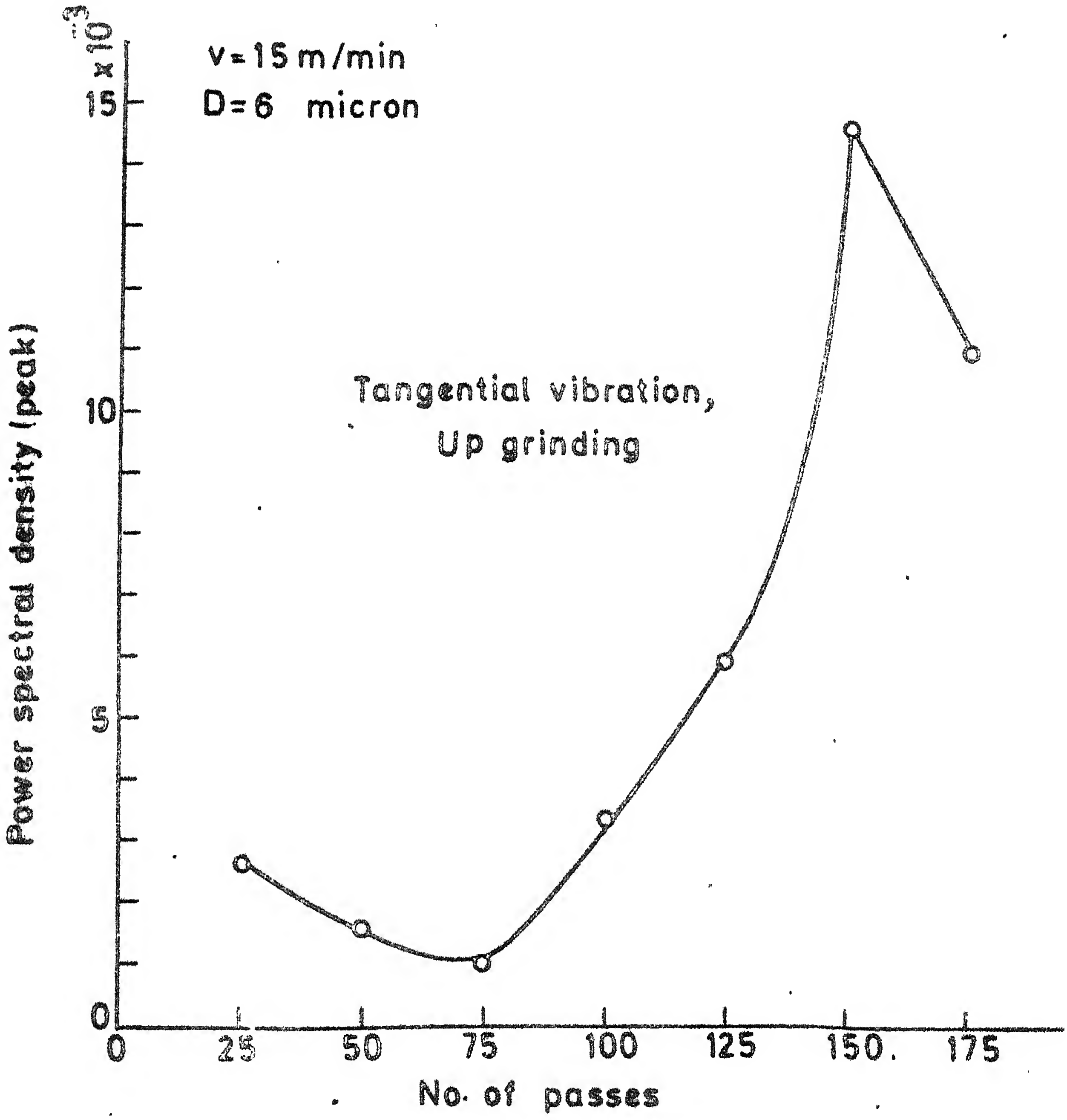


FIG. 20 VARIATION OF PSD WITH NO. OF PASSES

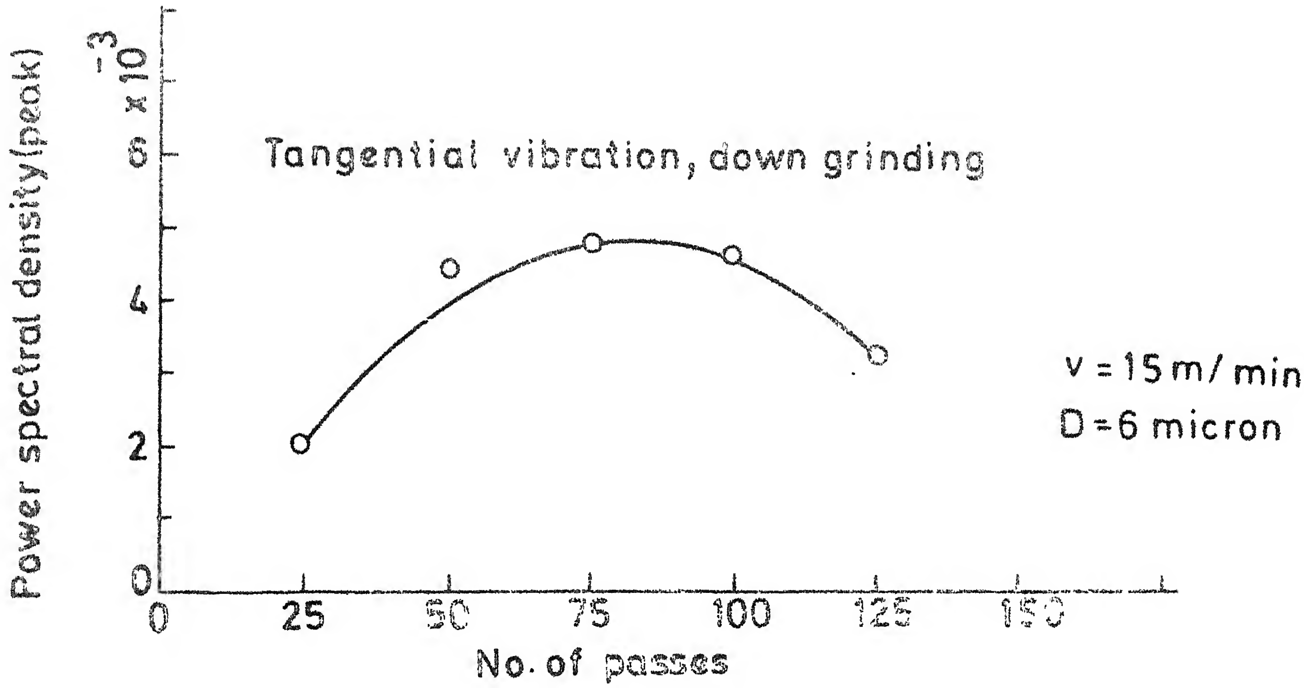


FIG.21 VARIATION OF PSD WITH NO. OF PASSES

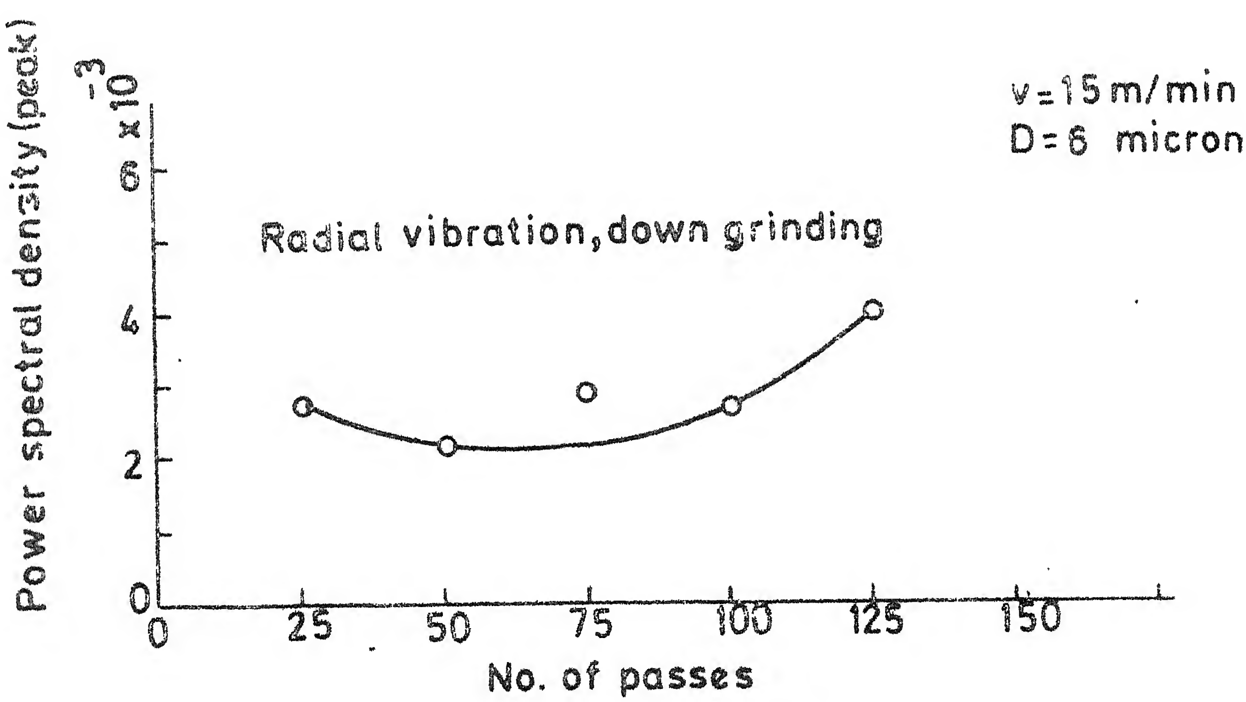


FIG.22 VARIATION OF PSD WITH NO. OF PASSES

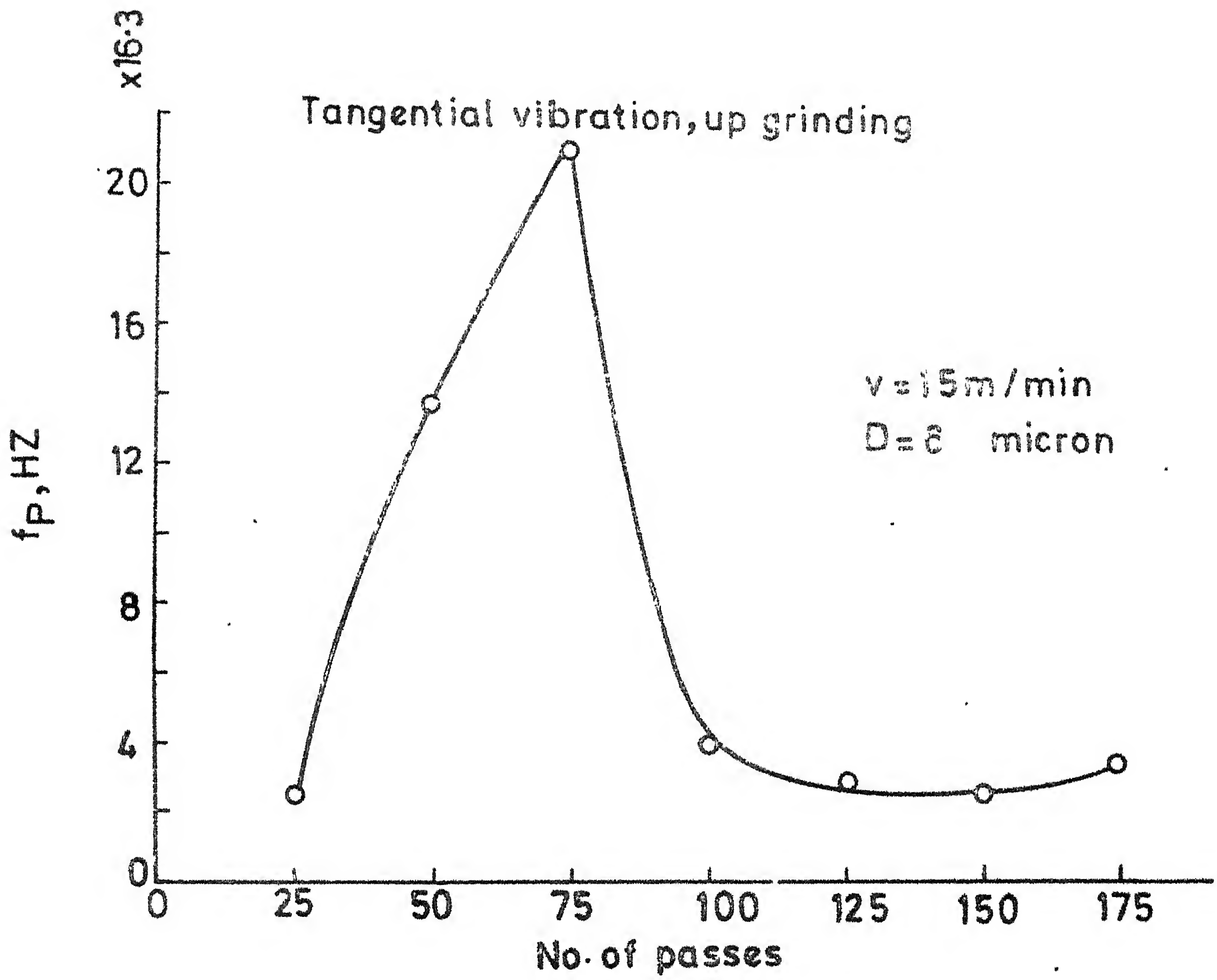


FIG.23 VARIATION OF f_p WITH NO. OF PASSES

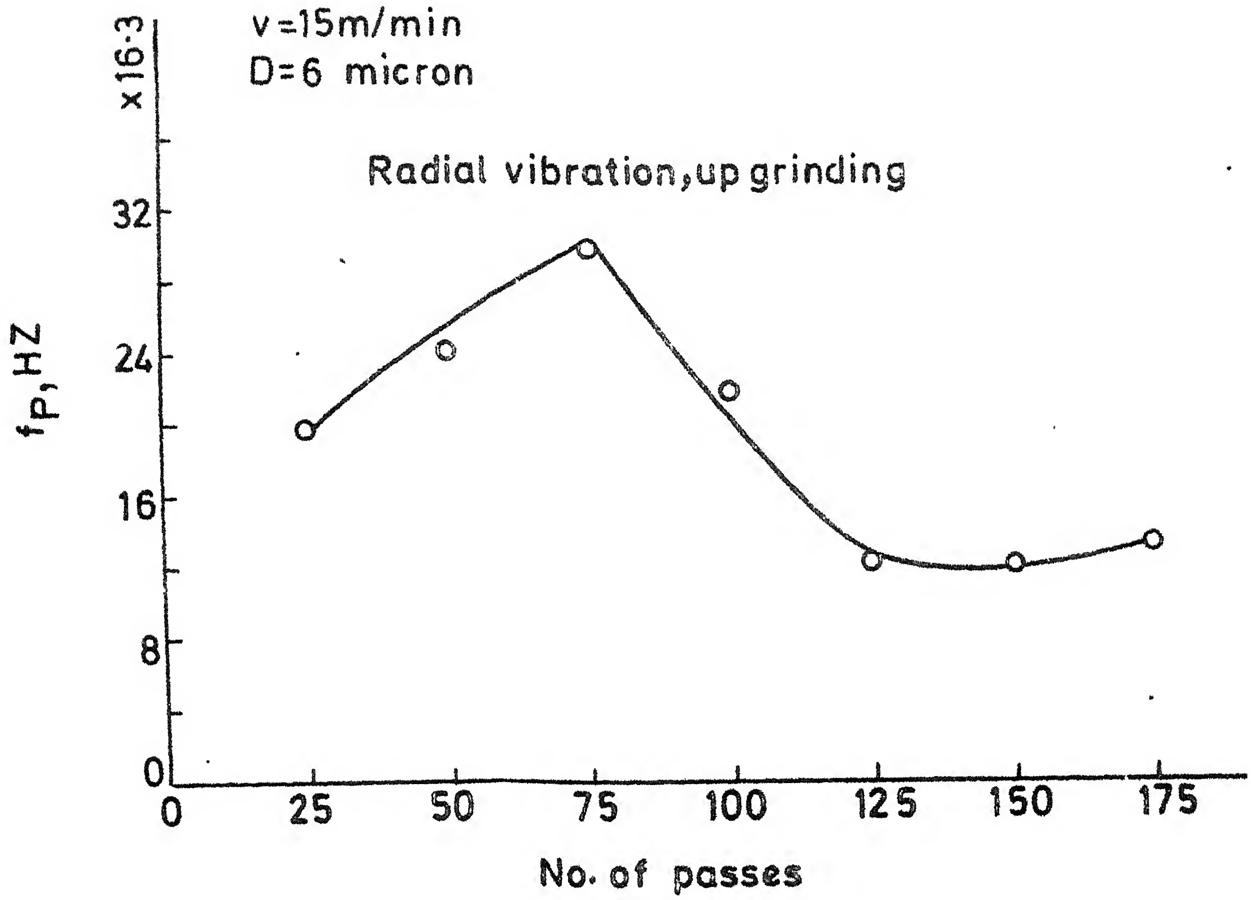


FIG.24 VARIATION OF fp WITH NO. OF PASSES

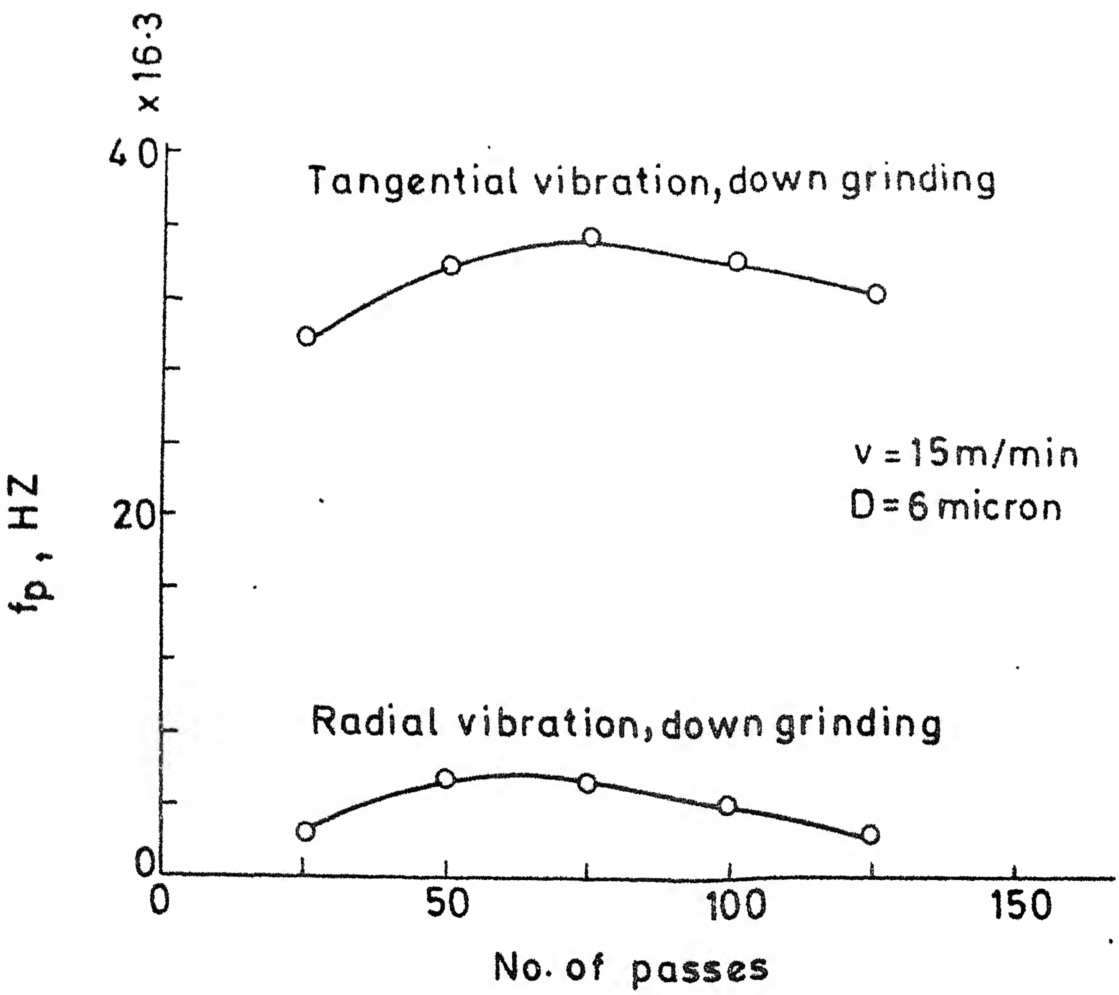


FIG.25 VARIATION OF f_p WITH NO. OF PASSES

APPENDIX-I

```
*************************************************************************
*       THIS PROGRAM IS FOR INITIALISING THE TAPE.                      *
*************************************************************************
// JOB
// FOR TEST
*IOCS(MAGNETICTAPE)
*NONPROCESS PROGRAM
*ONE WORD INTEGERS
      DATA IDOLR/@$$@/
      I1=0
      I2=0
      I3=0
      I4=0
      WRITE(4)IDOLR,I1,I2,I3,I4
      REWIND 4
      CALL EXIT
      END
// XEQ TEST
*CCEND
*************************************************************************
*       THIS PROGRAM IS FOR LOGGING IN THE ANALOG SIGNAL AND STORE      *
*       THE DATA IN THE DIGITISED FORM.                                 *
*************************************************************************
// JOB
// FOR LOG
*IOCS(KEYBOARD,MAGNETICTAPE,TYPEWRITER)
*ONE WORD INTEGERS
*NONPROCESS PROGRAM
      DIMENSION IDUMY(4)
      DATA IDOLR/@$$@/,IDUMY/4*0/
C     SEARCH FOR $$ RECORD
      CALL SRCH
C     ERASE THE $$ RECORD
      BACKSPACE 4
      WRITE(1,12)
12    FORMAT(5X,@LOGGING PROCEDURE STARTED@/)
      WRITE(1,10)
10    FORMAT(5X,@ENTER THE HEADER RECORD@/5X,@IN 5(I2,1X)FORMAT@/
     1,5X,@AFTER PROCEED LIGHT COMES@///)
      CALL BUSY
 5    READ(2,11)ID,IM,IY,ISM,ISD
11    FORMAT(5(I2,1X))
      CALL BUSY
      IF(ID)1,2,1
 2    IF(IM)1,3,1
 3    CONTINUE
      GO TO 4
 1    WRITE(1,11)ID,IM,IY,ISM,ISD
      WRITE(4)ID,IM,IY,ISM,ISD
      CALL FAST
      CALL PRESS
      GO TO 5
 4    WRITE(4)IDOLR,IDUMY
      REWIND 4
      WRITE(1,13)
13    FORMAT(@TODAYS LOGGING OVER SWITCH OFF THE SYSTEM@//)
      CALL EXIT
      END
*************************************************************************
*       THIS SUBROUTINE HELPS IN SEARCHING THE DATA UNDER THE HEADER    *
*       CONDITIONS.                                                     *
*************************************************************************
// FOR
      SUBROUTINE SRCH
      DATA IDOLR/@$$@/
      DIMENSION IDUMY(5)
```

```
      READ(1) 4
9     READ(1)IARAY
      IF(IARAY(I)-IPOINT)10,20,10
10    DO 11 J=1,5
      READ(1)
11    CONTINUE
      GO TO 9
20    RETURN
      END
// FOR
      SUBROUTINE TRANS
      DIMENSION IDATA(1000)
      IN=1
       IP=500
      DO 10 I=1,2
      WRITE(4)(IDATA(J),J=IN,IP)
      IN=IN+500
       IP=IP+500
10    CONTINUE
      RETURN
      END
// ASM
                                ENT       FAST
                        DATA    EQU      /3FFF
                        TEMP    BSS   E   2
                        AREA1   BSS       1
                        AREA2   BSS       1
                         POINT  DC        /100A
                         FAST   DC        *-*
                                STD       TEMP
                                STX   L1  XR1+1
                                STX   L2  XR2+1
                                STX   L3  XR3+1
                                LDX   L1  1000
                        START   LDX    2  15
                                LIBF      AIPJ
                                DC        /1100
                                DC        AREA1
                                DC        POINT
                                DC        0
                         LOOP1  LIBF      ALPJ
                                DC        0
                                MDX       LOOP1
                                LD        AREA1
                                STO   L1  DATA-1000
                        LOOP2    MDX   2  -1
                                MDX        LOOP2
                                MDX    1  -1
                                MDX       START
                         XR1    LDX   L1  *-*
                         XR2    LDX   L2  *-*
                         XR3    LDX   L3  *-*
                                LDD   L   TEMP
                                BSC   I   FAST
                                END
*****************************************************************************
*       THIS PROGRAM IS FOR PROCESSING DATA TO COMPUTE AUTO CORRELATION*
*       AND POWER SPECTRAL DENSITY POINTS.                                  *
*****************************************************************************
// JOB
// FOR PROCS
*IOCS(MAGNETICTAPE,TYPEWRITER,KEYBOARD,PLOTTER)
```

```
*  1 P  IOCS( ,  I,PA
*      IRD I   GR,
         DIMENSION IDUMY(5)

         DIMENSION Y(500)
         COMMON  IDATA(1000)
         DATA YES/3HY /
C        READ HEADER REC.
105      WRITE(1,15)
         CALL BUSY
15       FORMAT(41HTYPE IN HEADER RECORD IN 5(I2,1X)FORMAT)
102      READ (2,10)I0,I1,IY,IS1,IS2
         CALL BUSY
         IF(I0)110,110,111
110      WRITE(1,10)I0,I1,IY,IS1,IS2
10       FORMAT(5(I2,1X))
         CALL BUSY
         WRITE(1,16)
16       FORMAT(9HTYPE Y IF CORRECT)
         CALL BUSY
         READ (2,11) OK
11       FORMAT (A1)
         IF (OK-YES) 101,100,101
101      WRITE (1,12)
12       FORMAT (6HRETYPE HEADER)
         GO TO 102
100      CALL READH (I0,I1,IY,IS1,IS2,IND)
         IF (IND-1) 103,104,103
103      WRITE (1,14)
14       FORMAT (4HFOR GIVEN HEADER THERE IS NO RECORD,PLEASE TYPE CORRECT
     1   HEADER)
         RETURN 3
         GO TO 102
104      CALL READ
         IDUMY(1)=I0
         IDUMY(2)=I1
         IDUMY(3)=IY
         IDUMY(4)=IS1
         IDUMY(5)=IS2
         NP=400
         M=40
         CALL AUCPT(Y,NP,M)
C       PLOT OF AUTO CORRELATION
          CALL RPLOT(Y,NP,IDUMY)
         M1=M
          NP=1
         CALL POWER(Y,M1,NP)
         CALL RPLOT(Y,NP,IDUMY)
         GO TO 105
111      CALL EXIT
         END
****************************************************************************
*        THIS SUBROUTINE IS FOR PLOTTING THE COMPUTED VALUES OF AUTO-
*        CORRELATION AND POWER SPECTRAL DENSITY.
*        Y       =NUMBER OF POINTS TO BE PLOTTED ALONG Y AXIS
*        NP      =NUMBER OF POINTS TO PLOTTED ALONG X-AXIS.
*        IDUMY = HEADER CONDITIONS IN 5(I2,1X) FORMAT.
****************************************************************************
// FOR RPLOT
      SUBROUTINE RPLOT(Y,NP,IDUMY)
      DIMENSION Y(500),LABLX(10),LABLY(10),ITITL(30),IDUMY(5)
      MP=7
      XMIN=0.0
      XMAX=NP-1
```

```
C       FOR [illegible] CHOOSE THE [illegible]
C       Y [illegible] THE SCALE. IF [illegible]
C       ARE [illegible] FIXED, THEN ASSIGN PROPER VALUES FOR [illegible] AND Y [illegible]
C       AND [illegible] THE NEXT EIGHT CARDS.
         YMIN=Y(1)
         YMAX=Y(1)
        DO 350 I=2,NP
         IF(Y(I)-YMIN)100,200,200
100        YMIN=Y(I)
200     IF(Y(I)-YMAX)350,350,300
300     YMAX=Y(I)
350     CONTINUE
        WRITE(1,190)
190     FORMAT(41HTYPE LABEL OF X-AXIS IN 20 CHARACTERS (10A2))
        CALL BUSY
        READ(2,101)LABLX
101      FORMAT(10A2)
        WRITE(1,105)
105     FORMAT(41HTYPE LABEL OF Y-AXIS IN 20 CHARACTERS (10A2))
        CALL BUSY
        READ(2,101)LABLY
        WRITE(1,106)
        CALL BUSY
106     FORMAT([illegible])
        READ(2,107) ITLE
107     FORMAT(30A2)
C*****SCALING INFORMATION
        SX=8./(XMAX-XMIN)
        SY=6./(YMAX-YMIN)
        CALL SCALE ( SX,SY,XMIN,YMIN-3.0/SY)
C ****PLOTTING
        CALL FPLOT(1,XMIN,Y(1))
        DO 201 I=2,NP
        CALL FPLOT(2,FLOAT(I-1),Y(I))
201     CONTINUE
        CALL FPLOT(1,XMIN,YMIN)
        UX=(XMAX-XMIN)/16.
        UY=(YMAX-YMIN)/12.
        CALL FGRID(0,XMIN,YMIN,UX,16)
        CALL FGRID (1,XMAX,YMIN,UY,12)
        CALL FGRID(2,XMAX,YMAX,UX,16)
        CALL FGRID (3,XMIN,YMAX,UY,12)
        IF(XMAX*XMIN)10,20,20
10      CALL FPLOT(1,0.0,YMIN)
        CALL FPLOT(2,0.0,YMAX)
20      IF(YMAX*YMIN)30,40,40
30      CALL FPLOT(1,XMIN,0.0)
        CALL FPLOT(2,XMAX,0.0)
C***** X-AXIS ANNOTATION
40      A=XMIN
        DO 75 I=1,9
        CALL FCHAR(A-0.44/SX,YMIN-0.1/SY,.06,.08,4.712385)
        WRITE(MP,17)A
17      FORMAT(E11.4)
        A=A+2.*UX
75      CONTINUE
C***** X-AXIS LABELLING
        CALL FCHAR(XMIN+3./SX,YMIN-.96/SY,.1,.1,0.0)
        WRITE(MP,400)LABLX
400     FORMAT(10A2)
C***** WRITING THE TITLE FOR THE PLOT
        CALL FCHAR(XMIN,YMIN-1.26/SY,0.1,0.1,0.0)
        WRITE(MP,56)ITLE,(IDUMY(I),I=1,5)
56      FORMAT(1X,8F10.0,6X,30A2,I4,1H/,I2,1H/,I2,1H/,I2)
```

```
C***** Y-AXIS ANNOTATION
       A=YMAX
       DO 70 I=1,7
       CALL FCHAR(X-11-.75/SX,A-.04/SY,.08,.09,0.0)
       WRITE(NP,17)A
       A=A-2.*DY
70     CONTINUE
       CALL FCHAR(X-11-.91/SX,Y-1+1./SY,.1,.1,1.570795)
       WRITE(NP,100)LABEY
       CALL FPLOT(1,XMAX+1./SX,YMAX-2./SY)
       CALL FPLOT(2,XMAX+1./SX,YMAX-4./SY)
       CALL FPLOT(1,X 7X+3.5/SX,Y(T)-1./SY)
       RETURN
       END
*********************************************************************
*      THIS SUBROUTINE READS THE DIGITISED DATA FROM THE TAPE IN    *
*      STEPS OF 500 FOR THE GIVEN READING CONDITIONS.               *
*********************************************************************
// FOR
       SUBROUTINE READ
       COMMON IDATA(1000)
       IN=1
       IP=500
       DO 10 J=1,2
       READ(4)(IDATA(I),I=IN,IP)
       IN=IN+500
       IP=IP+500
10     CONTINUE
        RETURN
       END
*********************************************************************
*      THIS SUBROUTINE IS TO CONVERT THE DIGITISED DATA TO THE ACTUAL *
*      VALUE.                                                       *
*********************************************************************
// FOR
       SUBROUTINE AIDEN(Y, N, )
       DIMENSION Y(500)
       COMMON IDATA(1000)
       CNVRT=5./16384.
       DO 10 I=1,500
10     IDATA(I)=IDATA(I)/2
       DO 11 K=1,500
11     Y(K)=FLOAT(IDATA(K))*CNVRT
       CALL AUTOR(Y,N, )
       RETURN
       END
*********************************************************************
*      THIS SUBROUTINE READS THE VALUES X(DIGITISED DATA),COMPUTES  *
*      AUTO CORRELATION VALUES AND RETURNS IT.                      *
*      N = NUMBER OF SAMPLES TO BE CONSIDERED.                      *
*      M= NO OF CORRELATION POINTS.                                 *
*********************************************************************
// FOR
       SUBROUTINE AUTOR(X,N,M)
       DIMENSION X(500),ACORR(251)
       SUMX=0.0
       DO 40 J=1,N
       SUMX=SUMX+X(J)
40     CONTINUE
       XBAR=SUMX/FLOAT(N)
       SUMSQ=0.0
       DO 50 J=1,N
       SUMSQ=SUMSQ+(X(J)-XBAR)**2
50     CONTINUE
```

```
      SIGS=SUMS/FLOAT(L)
      K=1
60    A=1./(FLOAT(M)-FLOAT(K))
      SUM=0.
      I=M-K
      DO 70 J=1,I
      IK=J+K
      SUM=SUM+(X(J)-XBAR)*(X(IK)-XBAR)
70    CONTINUE
      K=K+1
      ACORR(K)=A*SUM/(SIGS**2)
      IF(K-M)60,80,80
80    L1=M+1
      DO 90 I=1,L1
      A(I)=ACORR(I)
90    CONTINUE
      RETURN
      END
*******************************************************************
*     THIS SUBROUTINE READS THE VALUES OF AUTO CORRELATION POINTS   *
*     AND RETURNS POWER SPECTRAL DENSITY VALUES.                    *
*     M1 = NUMBER OF SPECTRAL DENSITY POINTS.                       *
*     NP = TOTAL NUMBER OF POINTS ALONG AXIS.                       *
*******************************************************************
// FOR
      SUBROUTINE POWER(ACORR,M1,NP)
      DIMENSION PSDN(125)
      DIMENSION ACORR(251)
      M=M1
      L=2*M
       J=M
      DO 20 I=1,J
      SUM=0.
      DO 10 K=1,M
      K1=K+1
      SUM=SUM+ACORR(K1)*COS(2.*3.14159*FLOAT(I)*FLOAT(K)/FLOAT(L))
10    CONTINUE
      PSDN(I)=(ACORR(1)+2.*SUM)/FLOAT(L)
20    CONTINUE
      K=J-1
      DO 30 I=2,K
      K1=I-1
      ACORR(K1)=0.25*(PSDN(I+1)+PSDN(I-1))+0.50*PSDN(I)
30    CONTINUE
      NP=K1
      RETURN
      END
*******************************************************************
*     THIS SUBROUTINE HELPS IN LOCATING PARTICULAR DATA UNDER THE   *
*     GIVEN HEADER CONDITIONS IN 5(I2,1X) FORMAT.                   *
*******************************************************************
// FOR READH
      SUBROUTINE READH(ID,IM,IY,ISN,ISD,IND)
      DIMENSION IDUMY(5)
      DATA IDOLR/@$$@/
31    READ(3)IDUMY
      IF(IDUMY(1)-IDOLR)10,20,10
10    IF(IDUMY(1)-ID)21,22,21
22    IF(IDUMY(2)-IM)21,23,21
23    IF(IDUMY(3)-IY)21,24,21
24    IF(IDUMY(4)-ISN)21,25,21
25    IF(IDUMY(5)-ISD)21,26,21
26    IND=1
      WRITE(1,17)
```

```
17      F[illegible] PAGE [illegible])
        [illegible](1,15) [illegible]
15      FORMAT(5(I2,1X))
        RETURN
21      GO TO [illegible]
        REWIND 1
31      CONTINUE
        GO TO 31
2[illegible]      I[illegible]=0
        RETURN
        END
*DELETE              PROCS
*STORECI             PROCS PROCS
*LOCAL READ,READH,POWER,CATGPI,AUTOP
*CCEND
C       THE NEXT FOUR CARDS ARE USED FOR EXECUTING THE PROGRAM
-------------------------------------------------------------------------
// JOB
// XEQ DIG            FX
// JOB
// XEQ PROCS          FX
*************************************************************************
*       THIS PROGRAM IS FOR PLOTTING THE VIBRATION SIGNAL.THE LIMITS    *
*       CAN BE ASSIGNED IN THE PLOT SUBROUTINE.                         *
*************************************************************************
// JOB
// FOR RETRV
*IOCS(MAGNETICTAPE,TYPEWRITER,KEYBOARD,PLOTTER)
*NONPROCESS PROGRAM
*ONE WORD INTEGERS
        DIMENSION IDUMY(5)
        COMMON IDATA(1  )
        DATA YES/1HY/
C       READ HEADER NO.
105     WRITE(1,15)
        CALL BUSY
15      FORMAT('TYPE THE HEADER RECORD IN 5(I2,1X)FORMAT')
102      READ (2,10)ID,IM,IY,IST,ISQ
        CALL BUSY
        IF(ID)110,111,110
110     WRITE(1,10)ID,IM,IY,IS ,ISQ
10      FORMAT (5(I2,1X))
        CALL BUSY
        WRITE(1,16)
16      FORMAT('TYPE Y IF CORRECT')
        CALL BUSY
        READ (2,11) OK
11       FORMAT (A1)
        IF (OK-YES) 101,100,101
101     WRITE (1,12)
12      FORMAT ('RETYPE HEADER')
        GO TO 102
100     CALL READH (ID,IM,IY,IST,ISQ,IND)
        IF (IND-1) 103,104,103
103     WRITE (1,14)
14      FORMAT ('FOR GIVEN HEADER THERE IS NO RECORD. PLEASE TYPE CORRECT
      1 HEADER')
         REWIND 1
        GO TO 102
104     CALL READ
        IDUMY(1)=ID
        IDUMY(2)=IM
        IDUMY(3)=IY
        IDUMY(4)=IST
```

```
      IDUMY(5)=IS0
      CALL  SPLOT(IDUMY)
      GO TO 105
111   CALL EXIT
      END
// FOR
      SUBROUTINE SPLOT(IDUMY)
        DIMENSION IDUMY(5)
      DIMENSION Y(1000),LABLX(10),LABLY(10),ITITL(30)
      COMMON /     /IDATA(1000)
      CNVRT=5./16383.
      DO 10 I=1,1000
10    IDATA(I)=IDATA(I)/2
      DO 11 K=1,1000
11    Y(K)=FLOAT(IDATA(K))*CNVRT
      WRITE(1,100)
100   FORMAT(@TYPE LABEL OF X-AXIS OF 20 CHARACTERS OR LESS@)
      CALL BUSY
      READ(2,101)LABLX
101    FORMAT(10A2)
      WRITE(1,105)
105   FORMAT(@TYPE LABEL OF Y-AXIS OF 20 CHARACTERS OR LESS@)
      CALL BUSY
      READ(2,101)LABLY
      WRITE(1,106)
       CALL BUSY
106   FORMAT(@TYPE TITLE 30A2 FORMAT@)
      READ(2,107) ITITL
107   FORMAT(30A2)
      WRITE(1,5)
    5 FORMAT(@TYPE NO. OF POINTS FOR PLOTTING IN I3 FORMAT@)
      CALL BUSY
      READ(2,6)NP
    6 FORMAT(I3)
      CALL RPLOT(Y,NP,LABLX,LABLY,ITITL,IDUMY)
      RETURN
      END
// FOR
      SUBROUTINE READH(ID,IM,IY,IS1,IS2,IND)
      DIMENSION IDUMY(5)
      DATA IDOLR/@$$@/
31     READ(4)IDUMY
      IF(IDUMY(1)-IDOLR)10,20,10
10    IF(IDUMY(1)-ID)21,22,21
22    IF(IDUMY(2)-IM)21,23,21
23    IF(IDUMY(3)-IY)21,24,21
24    IF(IDUMY(4)-IS1)21,25,21
25    IF(IDUMY(5)-IS2)21,26,21
26    IND=1
      WRITE(1,17)
17    FORMAT(@DATA HEADER FOLLOWS@)
      WRITE(1,15) IDUMY
15    FORMAT(5(I2,1X))
      RETURN
21    DO 30 I=1,2
      READ(4)
30    CONTINUE
      GO TO 31
20    IND=0
      RETURN
      END
// FOR RPGHI
      SUBROUTINE RPLOT(Y,NP,LABLX,LABLY,ITITL,IDUMY)
      DIMENSION Y(1000),LABLX(10),LABLY(10),ITITL(30),IDUMY(5)
```

```
      N[illegible]
      XMIN=[illegible]
      XMAX=[illegible]
      YMIN=-5.0
      YMAX=5.0
C*****SCALING [illegible]
      SX=8./(XMAX-XMIN)
      SY=6./(YMAX-YMIN)
      CALL SCALE (SX,SY,XMIN,YMIN-3./SY )
C ****PLOTTING
      CALL FPLOT(1,X[illegible],Y(1))
      DO 201 I=1,NP
      CALL FPLOT(2,FLOAT(I-1),Y(I))
201   CONTINUE
      CALL FPLOT(1,X[illegible])
      DX=(XMAX-XMIN)/16.
      DY=(YMAX-YMIN)/12.
      CALL FGRID([illegible],XMIN,[illegible],DX,16)
      CALL FGRID(1,X[illegible],YMIN,DY,12)
      CALL FGRID(2,X[illegible]AX,[illegible]AX,DX,16)
      CALL FGRID(3,X[illegible],YMAX,DY,12)
      IF(XMAX*XMIN)10,20,20
10    CALL FPLOT(1,0.0,YMIN)
      CALL FPLOT(2,0.0,Y[illegible])
20    IF(YMAX*YMIN)30,40,40
30    CALL FPLOT(1,XMIN,0.0)
      CALL FPLOT(2,XMAX,0.0)
C*****  X-AXIS ANNOTATION
40    A=XMIN
      DO 75 I=1,9
      CALL FCHAR(A-[illegible]/SY,YMIN-0.1/SY,.06,.08,4.712385)
      WRITE(NP,17)A
17    FORMAT(F[illegible].1)
      A=A+2.*DX
75    CONTINUE
C*****  X-AXIS LABELLING
      CALL FCHAR(XMIN+3./SX,YMIN-.95/SY,.1,.1,0.0)
      WRITE(NP,400)LABELX
400    FORMAT(10A2)
C*****  WRITING THE TITLE FOR THE PLOT
      CALL FCHAR(XMIN,YMIN-1.26/SY,0.1,0.1,0.0)
      WRITE(NP,50)IPTTL,(IDUMY(I),I=1,5)
50    FORMAT(1X,8H[illegible],6X,30A2,T4,1H/,I2,1H/,T2,1H/,I2,1H/,T2)
C*****  Y-AXIS ANNOTATION
      A=YMAX
      DO 70 I=1,7
      CALL FCHAR(XMIN-.76/SX,A-.04/SY,.06,.08,0.0)
      WRITE(NP,17)A
      A=A-2.*DY
70    CONTINUE
      CALL FCHAR(XMIN-.[illegible]/SX,YMIN+1./SY,.1,.1,1.570795)
      WRITE(NP,400)LABELY
      CALL FPLOT(1,XMAX+1./SX,YMAX-2./SY)
      CALL FPLOT(2,XMAX+1./SX,YMAX-4./SY)
      CALL FPLOT(1,XMAX+3.5/SX,YMIN-3./SY)
      RETURN
      END
// FOR
       SUBROUTINE READ
      COMMON IDATA(1000)
      IN=1
      IP=500
      DO 10 J=1,2
      READ(4)(IDATA(I),I=IN,IP)
```

```
      IQ=I+4500
      IP=I+4500
 10   CONTINUE
      RETURN
      END
*[illegible]                         [illegible]
*CCEND
```

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